XA0055671

Selection and evaluation of gamma decay standards for detector calibration using coincidence method

Stanislav Hlaváč

Institute of Physics, 84228 Bratislava, Slovakia

Abstract

Coincidence method for calibration of gamma detectors using suitable calibration standards with two cascading gamma rays is analyzed. From the list of recommended gamma ray standards currently under reevaluation by the CRP, 14 radionuclides were selected as the potential source candidates for the coincidence method. The following sources were selected ^{24}Na, ^{46}Sc, ^{60}Co, ^{66}Ga, ^{75}Se, ^{88}Y, Nb^{94}, ^{111}In, ^{123m}Te, ^{133}Ba, ^{134}Cs, ^{152}Eu, ^{154}Eu and ^{207}Bi. Reaction ^{11}B (p,γ) ^{12}C* was also selected as a source of high energy gamma rays. Experimental data on angular correlation coefficients for selected sources were collected from the literature and evaluated according to the recommended procedure. Theoretical angular correlation coefficients were calculated and compared to the evaluated data.

1. Introduction

Coincidence method is being used successfully for decades in nuclear spectroscopy and various applications. It is considered to be the only feasible method to study complex decay and level schemes of atomic nuclei. Second very important and widely accepted application of coincidence method is determination of the absolute activity of standards for detector calibration. However, coincidence method is more general and allows to determine the absolute detector efficiency too.

At present the absolute calibration of photon detectors proceeds in two steps. In the first step determination of the absolute source intensity is performed usually by beta-gamma coincidence method. Result of this step is an absolutely calibrated standard, which is used in the second step for determination of absolute efficiency of the photon detector.

Use of the coincidence method can potentially reduce the number of steps in detector calibration procedure to a single step, reducing thus the uncertainty of the calibration. This possibility may be especially useful for several high energy photon sources (e.g. ^{24}Na, ^{11}B + p → ^{12}C*), which are difficult to calibrate absolutely.

2. Principle of the gamma-gamma coincidence method

The coincidence method is rather simple and can be used if the source nucleus decays by two cascading photons $\gamma_1$and γ_2. Simplified decay scheme of a nucleus with quantum numbers of decaying levels and gamma transitions is given in fig. 1. A general case with beta decay branches populating all levels of daughter nucleus is shown, where ei denotes feeding of level i in the daughter nucleus, b_i is a branching ratio of gamma ray γ_i, E_i is the level energy of the daughter nucleus, J^{π}_i, m_i are spin and magnetic substate of level i and $\lambda_i v_i$ is the multipolarity of γ_i radiation. Ideal source for coincidence method is a source with beta decay branch ε_2=1, populating only the second excited level with energy E_2 and both gamma ray branching ratios $b_{1,2}$=1.

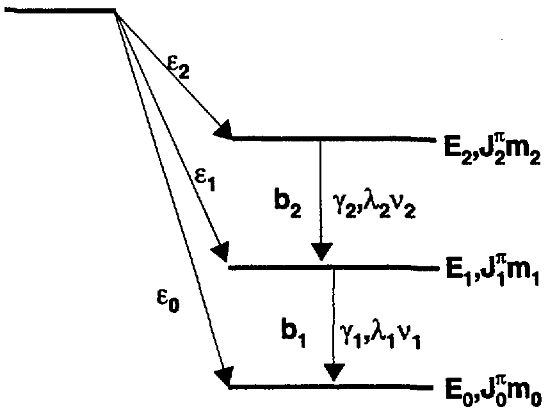

Fig. 1. Cascade of two gamma rays with mutlipolarities of both γ rays and characteristics of all levels involved. Symbols are explained in the text.

Numbers of photons γ_1 detected in detector d_1 (N_1), number of photons γ_2 registered in d_2 (N_2) and number of events (N_{12}) where both photons are registered in the respective detector can be written as follows

$$N_2 = A\omega_2 \frac{\varepsilon_2 b_2}{1+\alpha_2}$$

$$N_1 = A\omega_1 \frac{(\varepsilon_2 b_2 + \varepsilon_1) b_1}{1+\alpha_1}$$

$$N_{12} = A\omega_1\omega_2 \frac{\varepsilon_2 b_1 b_2}{(1+\alpha_1)(1+\alpha_2)} W(\vartheta) F(\omega_1\omega_2\vartheta)$$

where ω_1 and ω_2 are full energy peak efficiences, $W(\theta)$ is the angular correlation function and $F(\omega_1\omega_2\theta)$ is a correction for finite solid angle of both detectors.

Sources suitable for detector calibration using coincidence method were selected from the set of sources, recommended as calibration sources in the present CRP. The ideal source should have only two cascading γ-rays with β-decay feeding only the second excited level of the daughter nucleus. Therefore the main selection criteria were following:

- Two cascading γ rays $E_{\gamma 2}$ and $E_{\gamma 1}$ are emitted in the decay of parent nucleus
- β-decay branching to the second level E_2 in daughter nucleus ε_2 should be close to 100%
- β-decay branching to the first level E_1 in the in the daughter nucleus ε_1 should be minimal
- both γ-ray branching ratios B_1 and B_2 should be close to 100 %.

Sources selected from the whole set are given in the Tab. 1, all relevant data were taken from ref. 1. Together 14 radioactive sources covering energy region from 81 keV to 2754 keV were selected. In order to increase further the highest energy, we selected also a reaction $^{11}B(p,\gamma)^{12*}C$, which has a resonance at incident proton energy of 153 keV The excited final nucleus ^{12}C deexcite by emission of two high enegy γ rays with energies of 11670 keV and 4430 keV.

Parent	ε_2(%)	E_2(keV)	$E_{\gamma 2}$(keV)	B_2(%)	ε_1(%)	E_1(keV)	$E_{\gamma 1}$(keV)	B_1(%)
^{24}Na	99,94	4.122,90	2.754,03	99,94	0,00	1.368,70	1.368,63	100,00
^{46}Sc	100,00	2.009,80	1.120,55	99,99	0,00	889,30	889,28	100,00
^{60}Co	99,93	2.505,80	1.173,24	100,00	0,06	1.332,50	1.332,50	100,00
^{66}Ga	27,70	3.791,20	2.751,85	84,44	0,00	1.039,39	1.039,30	100,00
^{75}Se	95,80	400,70	136,00	64,62	<0,9	264,70	264,66	98,10
^{88}Y	94,90	2.734,10	898,04	100,00	5,50	1.836,10	1.836,06	100,00
^{94}Nb	98,10	1.573,70	702,62	100,00	0,00	871,10	871,09	100,00
^{111}In	90,00	416,70	171,28	100,00	0,00	245,40	245,40	100,00
^{123m}Te	--	247,60	88,46	100,00	--	159,10	158,97	100,00
^{133}Ba	86,00	437,00	356,02	86,93	<3,0	81,00	81,00	100,00
^{134}Cs	70,11	1.400,60	795,86	100,00	0,01	604,72	604,70	100,00
^{152}Eu	13,80	1.123,20	778,90	100,00	8,20	344,30	344,28	100,00
^{154}Eu	36,30	1.397,50	1.274,44	96,71	10,00	123,10	123,07	100,00
^{207}Bi	84,18	1.633,40	1.063,66	100,00	8,79	569,70	569,70	100,00
^{12*}C	100,00	16.105,80	11.670,00	92,00	0,00	4.438,90	4.430,00	100,00

Number of coincidenced events depends on angular correlation function $W(\theta)$, where θ is the angle between two γ-ray detectors. Angular correlation function depends on quantum characteristics of all involved levels i.e. on quantum numbers J^{π}_2, J^{π}_1 , J^{π}_0 and multipolarities $\lambda_i v_I$ of both γ-rays. Angular correlation function $W(\theta)$ can be calculated theoretically according to the following formulas (ref. 2)

$$W(\theta)=\Sigma A_{kk} P_k(\cos\theta)$$

$$A(J_2,\lambda_2,J_1,\lambda_1,J_0)=F_k(J_2,\lambda_2,J_1)\, F_k(J_0\lambda_1 J_1)$$

$$F_k(J_f,\lambda,J_i)=(-1)^{1-J_i-J_f}\,(2J_i+1)^{1/2}\langle\lambda 1\lambda\text{-}1|k0\rangle W(J_iJ_i\lambda\lambda;kJ_f),$$

where $P_k(\cos\theta)$ are Legendre polynomials, $\langle\lambda 1\lambda\text{-}1|k0\rangle$ are Clebsh-Gordon coefficients and $W(J_iJ_i\lambda\lambda;kJ_f)$ are Racah coefficients. The last formula holds for pure electromagnetic transitions, which can be generalized in the case of mixed multipole transitions

$$A_{kk}(J_i\lambda\lambda' J_f)=1/(1+\delta^2)[F_k(J_f\lambda\lambda J_i)+2\delta F_k(J_f\lambda\lambda' J_i)+\delta^2 F_k(J_f\lambda'\lambda' J_i)]$$

$$F_k(J_f\lambda\lambda' J_i)=(-1)^{1-J_i-J_f}\ [(2J_i+1)(2\lambda+1)(2\lambda'+1)]^{1/2}\langle\lambda 1\lambda' -1|k0\rangle W(J_iJ_i\lambda\lambda';kJ_f).$$

The angular correlation coefficients for all radionuclei given in Tab.1. were retrieved from literature and evaluated using statistical code lweigh. In two instances (^{24}Na, ^{46}Sc) no experimental data were found in the literature, for two another nuclei (^{111}In, ^{123m}Te) only single data on angular correlations were found. For all other nuclei several sources describing angular correlation measurements were found.

Data necessary for calculation of angular correlations coefficients for all nuclei are given in Tab. 2. In the last four columns of Tab.2 the angular correlation coefficients are given. Coefficients A_{22}^{theory} , A_{44}^{theory} are calculated according to formulas given above, using CERNLIB library (ref. 3) for Clebsh-Gordon and Racah coefficients. Coefficients A_{22}^{WM}, A_{22}^{WM} are weighted means calculated with the code lweight (ref. 4). The agreement between experimental and theoretical values is reasonable in all instances except for ^{154}Eu, where theoretical coefficients predict higher anisotropy.

References

1. R. B. Firestone, V. S. Shirley, eds., Table of Isotopes, J. Wiley, 1996.
2. H. Frauenfelder, R. M. Steffen, Angular correlations in K. Siegbahn, ed. α-, β- and γ-ray spectroscopy, North Holland, 1968, Vol2., p. 997.
3. CERNLIB, CERN Geneva, 2000.
4. G. Helmer (M. Herman), private communication, May 1999.

Parent	Daughter	J^{π}_2	$\lambda_2\nu_2$	δ_2	J^{π}_1	$\lambda_1\nu_1$	δ_1	J^{π}_0	A_{22}^{theory}	A_{44}^{theory}	A_{22}^{WM}	A_{44}^{WM}
^{24}Na	^{24}Mg	4^+	?	-	2^+	E2	-	0^+	0.1020	0.0091	-	-
^{46}Sc	^{46}Ti	4^+	E2	-	2^+	E2	-	0^+	0.1020	0.0091	-	-
^{60}Co	^{60}Ni	4^+	E2(+M3)	-0.0025	2^+	E2	-	0^+	0.1020	0.0091	0.1012(22)	0.0658(24)
^{66}Ga	^{66}Zn	1^+	M1+E2	?	2^+	E2	-	0^+	-0.2455	0.0000	-	-
^{75}Se	^{75}As	$5/2^+$	E1	-	$3/2^-$	M1+E2	-0.044(6)	$3/2^-$	-0.0331	0.0000	-0.028(4)	0.0015(18)
^{88}Y~	^{88}Sr	3^-	E1	-	2^+	E2	-	0^+	-0.0714	0.0000	-0.0692(32)	0.0009(19)
^{94}Nb	^{94}Mo	4^+	E2	-	2^+	E2	-	0^+	0.1020	0.0091	0.0968(34)	0.0141(38)
^{111}In	^{111}Cd	$7/2^+$	M1+E2	-0.144(3)	$5/2^+$	E2	-	$1/2^+$	0.0312	-0.0014	-	-
^{123m}Te	^{123}Te	$11/2^-$	M4	-	$3/2^+$	M1+E2	0.062(6)	$7/2^-$	-0.1203	0.0000	-	-
^{133}Ba	^{133}Cs	$1/2^+$	E2	-	$5/2^+$	M1+E2	-0.151(2)	$7/2^+$	0.0359	-0.0016	0.0369(17)	0.0036(11)
^{134}Cs	^{134}Ba	4^+	E2	-	2^+	E2	-	0^+	0.1020	0.0091	0.0993(90)	0.0050(17)
^{152}Eu	^{152}Gd	3^-	E1(+M2)	0.002	2^+	E2	-	0^+	-0.0730	0.0000	-0.0730(19)	0.002(7)
^{154}Eu	^{154}Gd	2^-	E1+M2	0.032(15)	2^+	E2	-	0^+	0.2731	0.0003	0.123(13)	0.005(2)
^{207}Bi	^{207}Pb	$13/2^+$	M4	-	$5/2^-$	E2	-	$1/2^-$	0.2208	-0.0180	0.224(29)	-0.023(17)
^{11}B	^{12*}C	2^+	M1	-	2^+	E2	-	0^+				