^{155}Eu – Comments on evaluation of decay data

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1. DECAY SCHEME

The ^{155}Eu decay scheme is complete. The most intense allowed β^--transitions occur to the excited levels with energy of 105.31 keV (46.1%) and 86.55 keV (25.5%).

The 1st forbidden β^--transitions populate the 60.01 keV (9,2%) and 146.07 keV (1.9%) levels.

The ground state in ^{155}Gd is populated by the intense allowed β^--transition (16.6%).

The 2nd forbidden β^--transition to the excited level of 107.58 keV was not observed. From the log ft systematics its log ft should be more than 11.1 and the upper limit on this β^- branch intensity is expected less than 0.01%.

2. NUCLEAR DATA

Q value is from 1995Au04 .

The evaluated value of the ^{155}Eu half-life has been taken from 2000Ch01 (Chechev and Egorov). It is based on the measurement results given in Table 1.

Table 1. Set of experimental data for the evaluation of ^{155}Eu half-life (in days)

Reference	Author	Data set "1" χ^2 =334.9 $(\chi^2)_6^{0.05}$ =14.1	Data set "2" χ^2 =6.14 $(\chi^2)_5^{0.05}$ = 12.6	Data set "3" χ^2 =5.68 $(\chi^2)_5^{0.05}$ =12.6
1998Si12	Siegert *et al.*	1739(8)	1739(8)	1739(8)
1993Th04	Thompson *et al.*	1735(22)	1735(22)	1735(22)
1992Un01	Unterweger *et al.*	1739.0(5)	1739.0(5)	1739(7)[b]
1983Wa26	Walz *et al.*	1737(23)	1737(23)	1737(23)
1974Da24	Daniels *et al.*	1708(18)	1708(18)	1708(18)
1972Em01	Emery *et al.*	1812(4)	Omitted [a]	-
1972Su09	Subba Rao	1653(51)	1653(51)	1653(51)
1970Mo23	Mowatt *et al.*	1698(74)	1698(74)	1698(74)

[a] The value from 1972Em01 has been omitted on the basis of statistical considerations.

[b] The rule of “50% weight”(LRSW) leads to a significant increase of the 1992Un01 uncertainty.

In 2002Un02 the new NIST measurement result was published for the ^{155}Eu half-life: $T_{1/2}$ = 1739.06(45) d. It does not differ practically from 1992Un01 and its use instead of 1992Un01 does not change this evaluation.

The weighted mean of the experimental values from the final data "set 3" is 1736(5) days where the uncertainty is internal. The adopted value of the ^{155}Eu half-life is 1736(5) days, or 4.753(14) years.

2.1. b^{-}-Transitions

The energies of the β^- transitions have been computed from the Q value and the level energies adopted from 1986Sc25, where the reaction ^{154}Gd(n,γ)^{155}Gd was studied. For the level energies see also the evaluation in Nuclear Data Sheets (1994Re10).

The probabilities of the β^- transitions have been obtained from the $P_{\gamma+ce}$ balance for each level based on the P_γ normalization factor of 0.307(3) (see sect.4.2.3). The calculated P($\beta_{0,0}$) agrees with the unweighted mean of 18(4)% of the five measurement results of 1949Ma58, 1954Le08, 1956Du31, 1959Am16, 1960Su04.

2.2. Gamma Transitions and Internal Conversion Coefficients

The evaluated energies of gamma transitions are energies of gamma rays (E_γ) with adding the recoil energy of E_γ^2 / $2Mc^2$ where M – mass of the ^{155}Gd nucleus. The latter changes the energy only for $\gamma_{6,0}$.

The gamma transition probabilities have been calculated from the gamma emission probabilities and the internal conversion coefficients (ICC).

For gamma transitions with energies more than 25 keV the ICC have been evaluated using theoretical values from 1978Ro22 for the adopted multipolarities. For these transitions the following uncertainties for theoretical values have been adopted 1% for α_K and 3% for α_L , α_M, α_{NO}. The ICC interpolated from other tables (1968Ha53, 1978Band) do not differ from the evaluated values within limits of adopted uncertainties.

For low-energy gamma transitions $\gamma_{5,4}$, $\gamma_{3,2}$, $\gamma_{4,2}$ the ICC have been evaluated using theoretical values from 1993Ba60. The ICC values in 1968Ha53 and 1978Ro22 for these energies differ considerably or are absent.

The adopted E2 admixtures for (M1+E2)-transitions $\gamma_{5,4}$, $\gamma_{3,2}$, $\gamma_{5,2}$, $\gamma_{1,0}$ and $\gamma_{2,0}$ have been evaluated using measurement results from 1959De29, 1961Su13, 1962Ha24, 1966As02, 1967Fo11, 1967Ko12, 1975Ch04, 1975Kr04, 1986Sc25 and 1990GoZS. In these works the intensity ratios L_1:L_2:L_3 were measured for conversion electrons in decays of ^{155}Eu and ^{155}Tb and also in the ^{154}Gd(n,γ) reaction. Also $\gamma\gamma(\theta)$-correlations were studied in ^{155}Tb decay and in Coulomb excitation of the ^{155}Gd levels - ^{155}Gd (p, p' γ) (see Table 2).

Table 2. Measured and evaluated E2 admixtures for the (M1+E2) multipolarities of gamma transitions in the decay of ^{155}Eu

E_γ, keV	Measurement result, % E2	NSR code	Method	Evaluated (adopted) value, % E2
10.418	0.11(5) 0.4(3)	1975Ch04 1967Fo11	L_1; L_2; L_3, ^{155}Tb L_1; L_2; L_3, ^{155}Eu	0.11(5)
18.763	7.4(6) 6.3(8) 7.1(4) 5.6(12) 6.3(14)	1990GoZS 1967Fo11 1975Ch04 1962Ha24 1975Kr04	L_1; L_2; L_3, ^{155}Eu L_1; L_2; L_3, ^{155}Eu L_1; L_2; L_3, ^{155}Tb L_1; L_2; L_3, ^{155}Tb $\gamma\gamma$, ^{155}Eu	7.1(4) WM
31.444	17(5)	1986Sc25	L_1; L_2; L_3, ^{154}Gd(n,γ)	17(5)

60.009	4.0(4) 3.3(10) 4.4(4) 3.7(10) 3.5(9) 3.8(10) 4.9(24)	1967Fo11 1967Ko12 1986Sc25 1962Ha24 1975Kr04 1961Su13 1966As62	L_1; L_2; L_3, ^{155}Eu L_1; L_2; L_3, ^{155}Tb L_1; L_2; L_3, ^{154}Gd(n,γ) L_1; L_2; L_3, ^{155}Tb γγ, ^{155}Eu γγ, ^{155}Eu ^{155}Gd (p, p' γ)	4.1(4) WM
86.059	2.5(6) 3.5(10) 4.9(15) 3.5(16)	1986Sc25 1975Kr04 1966As02 1959De29	L_1; L_2; L_3, ^{154}Gd(n,γ) γγ, ^{155}Eu ^{155}Gd (p, p' γ) ^{155}Gd (p, p' γ)	3.0(6) WM

3. ATOMIC DATA

3.1. Fluorescence yields

The fluorescence yields are taken from 1996Sc06 (Schönfeld and Janβen).

3.2. X Radiations

The X-ray energies are based on the wavelengths in the compilation of 1967Be65 (Bearden). The relative KX-ray emission probabilities are taken from 1996Sc06, 1999Schönfeld and 1974Sa28.

3.3. Auger Electrons

The energies of Auger electrons are from 1977La19 (Larkins) and 1987Table.
The ratios P(KLX)/P(KLL) and P(KLY)/P(KLL) are taken from 1996Sc06.

4. PHOTON EMISSIONS

4.1 X-Ray Emissions

The total absolute emission probability of KX-rays (P_{XK}) has been computed using the adopted value of ω_K and the evaluated total absolute emission probability of K conversion electrons Pce_K = 25.17(46) per 100 disintegrations. The absolute emission probabilities of the KX-ray components have been computed from P_{XK} using the relative probabilities from Sect.3.2.

The measured values of the total absolute emission probability of KX-rays given below can be compared to the calculated (adopted) value of $P_{XK}^{eval.}$ = **23.6(5)** per 100 disintegrations:

1967Fo11	1967Bl11	1968Om01	1969Me09	1971Ge11	1994Eg01	WM
22.9(10)	25.2(25)	21.3(23)	21.1(6)	22.5(12)	23.50(19)	23.3(2) [a]

[a] Weighted mean of all 6 values. The value of 1969Me09 gives the 80% contribution to χ^2. With omitting this value the weighted mean of 5 values is 23.5(2).

The total absolute emission probability of LX-rays has been computed using the adopted values of ϖ_L and n_{KL} and the evaluated values of $P(ce_K)$ =25.17(46) and $P(ce_L)$ = 21.2(24)%.

4.2. Gamma–Ray Emissions

4.2.1. Gamma–Ray Energies

The measured and evaluated values of gamma ray energies are given in Table 3.

The evaluated values of Eγ have been obtained as weighted means omitting outliers contradicting to the energies of excited levels measured in 1986Sc25. The values of 1969Me09 have been omitted as the author in 1990Me15 replaces them.

4.2.2. Gamma–Ray Relative Emission Probability

The measured and evaluated values of relative gamma ray emission probabilities (P′γ) are shown in Table 4.

The evaluated values of P′γ have been obtained as weighted means apart from P′($\gamma_{5,4}$) and P′($\gamma_{4,2}$). The P′($\gamma_{5,4}$) has been evaluated from the intensity balance for the 107.58 keV- level. The P′($\gamma_{4,2}$) has been calculated from data on conversion electrons (1967Fo11) and the adopted ICC using the measured in 1967Fo11 ratio P($ce_{4,2}$ L3)/P($ce_{3,0}$ K) = 0,115(6) and the adopted values of $\alpha_{L3}(\gamma_{4,2})$ and $\alpha_K(\gamma_{3,0})$.

The values of 1969Me09 have been omitted as the author in 1990Me15 replaces them. Other values have been omitted due to absence of uncertainties or as statistical outliers.

Our evaluated value P′($\gamma_{3,0}$) = 68.8(14) for the intense gamma ray with energy of 105.31 keV is supported by the results of measurements of the intensity ratio P($ce_{3,0}$ K)/ P($ce_{2,0}$ K) = 0.408(8) in 1967Fo11 (see Table 5) which leads to the value P′($\gamma_{3,0}$) = 68.7(17) if the adopted α_K in sect.2.2 is used.

4.2.3. Gamma-Ray Absolute Emission Probabilities

Two absolute measurements of the emission probability are available for the 86,55 keV gamma ray: 31.1(4)% in 1994Co02 and 30.5(3)% in 1994Eg01. The weighted mean of these values has been adopted as the evaluated P($\gamma_{2,0}$) = 30.7(3)%. Here the uncertainty is the external one of WM.

The absolute emission probabilities of other gamma rays have been computed from the evaluated emission probabilities (P') given in Table 4 and the evaluated absolute emission probability of $\gamma_{2,0}$ (86.55 keV).

It should be noted that the absolute emission probability of $\gamma_{3,0}$ (105.31 keV) was measured in 1992Sa04: P($\gamma_{3,0}$) = 20.39(13) %. This value is considerably less than the evaluated one and measured in 1994Eg01 and 1996Ch27. If it is adopted without changing of the evaluated P($\gamma_{2,0}$) = 30.7(3)% the relative emission probability of $\gamma_{3,0}$ will be 66.4(9), essentially less than the average of the eight measurement results (Table 4 and comment in sect.4.2.2.). On other hand, if the value of 1992Sa04 is adopted together with the evaluated P'($\gamma_{3,0}$) = 68.8(14), the P($\gamma_{2,0}$) will be obtained as 29.6(6) %, less than both results of direct measurement of the absolute emission probability of this gamma ray (1994Co02 and 1994Eg01).

Therefore we consider the value of 1999Sa04 as too small and do not take it into account.

Table 3. Measured and evaluated values of gamma ray energies in the decay of ^{155}Eu

	1959Ha07	1967Fo11	1969Me09	1970Re08	1970Ra37	1975Ch04[a]	1975Kr04	1986Sc25 [b]	1990Me15	1990GoZS	Evaluated (adopted) value
$\gamma_{5,4}$		10.40(2)*				10.40(2)*		10.4183(13)			10.4183(13)
$\gamma_{3,2}$		18.776(35)*	18.776(35)*			18.749(19)*	18.73(3)*	18.760(4)	18.784(35)*	18.764(2)	18.763(2) [c]
$\gamma_{4,2}$		21.02(2)				21.02(2)		21.030(10)		21.036(4)	21.035(4)
$\gamma_{2,1}$			26.513(21)*				26.49(5)	26.530(23)	26.532(21)		26.531(21)
$\gamma_{5,2}$			31.40(10)*	31.55(12)				31.444(7)	31.40(10)		31.444(7)
$\gamma_{3,1}$	45.29(1)	45.3(2)*	45.299(13)*	45.299(2)	45.2972(13)		45.27(5)*	45.3000(10)	45.295(13)		45.2990(10)
$\gamma_{5,1}$			57.983(30)*	57.970(26)	57.9805(20)		57.99(4)	57.989(1)	57.986(30)		57.989(1)
$\gamma_{1,0}$	60.00(2)		60.019(15)*	60.006(4)	60.0100(18)		60.01(4)	60.008(2)	60.022(15)	60.0086(10)	60.0086(10) [c]
$\gamma_{6,1}$		86.01(20)	86.0(5)	86.062(23)	86.062(5)		86.03(7)	86.0590(10)			86.05910(10)
$\gamma_{2,0}$	86.56(1)	86.82(20)	86.539(15)*	86.541(3)	86.5452(33)		86.53(3)	86.5470(10)	86.554(15)		86.5479(10)
$\gamma_{3,0}$	105.32(3)	105.28(20)	105.315(15)*	105.302(4)	105.308(3)		105.30(3)	105.3090(10)	105.338(15)		105.3083(10)
$\gamma_{3,0}$			146.05(2)*	146.061(5)			146.04(10)	146.0710(10)	146.090(90)		146.0710(10)

[a] Decay of ^{155}Tb
[b] Reaction ^{154}Gd(n,γ)^{155}Gd
[c] The data of 1976Me10 (decay of ^{155}Tb) have been taken into consideration additionally: E($\gamma_{3,2}$)=18.769(15) keV and E($\gamma_{1,0}$)=60.012(3) keV.
* Omitted from averaging. Values of 1969Me09 are superseded by those of 1990Me15.

Table 4. Measured and evaluated values of relative gamma ray emission probabilities in the decay of ^{155}Eu.

	Eγ, keV	1959Ha07	1967Be11	1968Al01	1969Me09	1970Re08	1971Ge11	1975Kr04	1990Me15	1994Eg01	1996Ch27	Evaluated value
$\gamma_{5,4}$	10.418											0.0115(13) [a]
$\gamma_{3,2}$	18.763	≈0,1*			0.16(4)*		0.17(3)	0.13(3)	0.16(4)			0.16(2) [b,c]
$\gamma_{4,2}$	21.035											$1.5(3)\cdot10^{-3}$ [d]
$\gamma_{2,1}$	26.531	≈4*		≈1*	1.03(6)*		1.00(10)	1.10(13)	1.03(6)			1.03(6) [c]
$\gamma_{5,2}$	31.444				0.023(5)*	0.03(2)			0.023(5)			0.023(5) [c]
$\gamma_{3,1}$	45.299	2.3*		2.8(7)*	4.18(17)*	3.6(7)	4.1(3)	3.95(40)	4.21(20)	4.36(12)	4.3(10)	4.27(12) [c]
$\gamma_{5,1}$	51.989			0.20(3)	0.217(18)*	0.22(5)		0.23(3)	0.221(18)	0.213(30)		0.217(18) [c]
$\gamma_{1,0}$	60.009	4,0*	5.1(20)*	3.8(2)	3.60(10)*	4.3(3)	3.9(9)	3.8(4)	3.60(10)	3.99(12)	3.9(9)	3.96(12) [c]
$\gamma_{6,1}$	86.059			0.50(5)		0.49(5)		0.54(11)				0.50(5) [c]
$\gamma_{2,0}$	86.548	100	100	100	100	100	100	100	100	100	100	100
$\gamma_{3,0}$	105.308	64*	65.7(65)	67.9(35)	66.8(27)*	68.3(27)	68(4)	69.9(35)	66.8(27)	68.5(14)	69.5(16)	68.8(14) [c,e]
$\gamma_{6,0}$	146.071		0.16(5)		0.167(10)*	0.19(2)		0.14(2)	0.167(10)			0.166(10) [c]

[a] Evaluated from the intensity balance for the 107.58 keV level

[b] In addition the value of 0.16(2) from 1974HeYW has been taken into account

[c] Weighted mean

[d] Evaluated from the conversion electron intensity and ICC

[e] In addition the value of 69.1(9) from 1982Co05 has been taken into account

* Omitted from averaging. Values of 1969Me09 are superseded by those of 1990Me15.

5. ELECTRON EMISSIONS

The energies of the conversion electrons have been calculated from the gamma-transition energies given in 2.2 and the electron binding energies.

The emission probabilities of the conversion electrons have been calculated using the evaluated Pγ and ICC. In Table 5 the relative intensities of conversion electrons P'ce(exp.) measured in 1967Fo11 are compared to the relative intensity values P'ce(calc.) calculated from the evaluated absolute emission probabilities (in units P'($ce_{3,0}$ K) = 1000).

Table 5. Comparison of experimental and calculated values of relative intensity of conversion electrons in the ^{155}Eu decay.

	Energy, keV	P'ce(exp)	P'ce(calc.)
$ec_{5,4}$ L	2.043-3.175	305(27)	206(30)
$ec_{1,0}$ K	9.770(3)	1870(100)	2000(130)
$ec_{3,2}$ L	10.387-11.520	2730(110)	3080(400)
$ec_{4,2}$ L	12.659-13.792	212(8)	218(30)
$ec_{6,1}$ K	35.820(3)	66(5)	91(12)
$ec_{2,0}$ K	36.309(3)	2450(50)	2440(50)
$ec_{3,1}$ L	36.923-38.053	90(5)	100(5)
$ec_{1,0}$ L	51.633-52.766	420(10)	418(16)
$ec_{3,0}$ K	55.069(3)	1000	1000
$ec_{2,0}$ L	78.172-79.305	380(9)	382(13)
$ec_{3,0}$ L	96.933-98.066	152(6)	152(8)

As seen from Table 5 the experimental and calculated values agree well with the exception of $ec_{5,4}$ L and $ec_{6,1}$ K. The disagreement for $ec_{5,4}$ L can be connected with experimental difficulties of measurement of the 2-3 keV conversion electrons on the background of intense L Auger electrons, and for $ec_{6,1}$ K – of measurement on the background of intense conversion line of $ec_{2,0}$ K.

The total absolute emission probability of K Auger electrons has been computed using the total P(ce_K) = 25.17(46) % and the adopted ω_K in sect.3.

The total absolute emission probability of L Auger electrons has been computed using the evaluated total P(ce_K) and P(ce_L) = 21.2(24) % and the adopted ϖ_L and n_{KL} in sect.3.

The values of β^- average energies have been calculated using the LOGFT program.

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