^{229}Th – Comments on evaluation of decay data by G. Mukherjee

This evaluation was completed in May 2011, and the literature available at this date has been included here. ^{229}Th is a member of the ^{233}U decay series. This was recognized by Hagemann et al. (1947Ha02). ^{233}Th β^- decay → ^{233}Pa β^-decay → ^{233}U α decay → ^{229}Th.

1. Decay Scheme

^{229}Th is a part of the 4n+1 series of Neptunium decay chain which decays 100 % by the emission of α particles to the ground and the excited states in ^{225}Ra. 5 (1) % populates the ground state of ^{225}Ra. Important impurities in the production of ^{229}Th are U-238 and U-232.

The decay scheme is reasonably complete and consistent. Its overall consistency is verified by the comparison between Q(calc), deduced from the evaluated average energies of all emissions, and Q(alpha) from the atomic mass evaluation of Audi et al. (2003Au03). A percentage deviation between Q(calc) and Q(alpha) is 0.32 %. There are, however, 26 unplaced gamma rays observed in this decay scheme. The level energies, spins, parities along with the multipolarities and mixing ratios of the γ-rays presented in this evaluation are from 2009Ja03.

2. Nuclear Data

The Q value (5167.6 ± 1.0 keV) is from the atomic mass evaluation of Audi et al. (2003Au03). The experimental half-life values of ^{229}Th are given in Table-1

Table-1: Experimental values of ^{229}Th half-life

Reference	$T_{1/2}$ Values (10^3 a)	comments
1947HA02	7	Not used
1947EN03	5	Not used
1950HA52	7.340 (217)	Indirect method. 2 % greater $T_{1/2}$ used for ^{233}U. Modified uncertainty.
1989GO19	7.880 (120)	Isotope dilution mass spectrometry.
Recommended value	**7.88 (12)**	**Value reported by 1989GO19**

The experimental half-life values of ^{229}Th are given in Table 1. The first measurement available in the literature is by 1947Ha02 and 1947En03 who reported a value of 7 10^3 a and 5 10^3 a respectively without the uncertainty or the details of the measurement. These values have been excluded from the averaging. The value reported in 1950Ha52 was an indirect method done in 1950. Known amount of ^{233}U was allowed to decay for a measured period of time and then the activity of the daughter ^{229}Th was determined. 1989Go19 had measured specific activity with mass spectrometry. This value is about 7 % larger than 7340 (160) a reported in 1950Ha52. In the later one, they used a half-life of 1.62 10^5 a for ^{233}U which is about 2 % greater than the presently adopted value. Consequently, an extra uncertainty of 2 % must be included in that value. Still there remains a discrepancy of about 5 % which may be due to an underestimation of the effect of impurities. Considering these, the experimental value of 7.880 (120) 10^3 a reported in 1989GO19 has been recommended by the evaluator. The compilation of 1979Ry03 and 1991Ry01 give a value of 7.3 10^3 a for the half life of ^{229}Th.

The experimental half-life values of the daughter nucleus ^{225}Ra (decays by β^- decay) are given in Table 2. The first measurement available in the literature is by 1947Ha02 who reported a value of 14.8 d without uncertainty or the details of the measurement. This value has been excluded from the averaging.

Table-2: Experimental values of ^{225}Ra half-life

Reference	$T_{1/2}$ Values (d)	comments
1947Ha02	14.8	Not used.
1950Ha52	14.8 (2)	Indirect method; following growth and decay of α-activity. $T_{1/2}$ = 10 d assumed for the daughter ^{225}Ac
1987Mi10	15.02 (56)	Photo disintegration of ^{232}Th.
Recommended value	**14.82 (19)**	**LWEIGHT, Reduced χ^2 = 0.14**

The computer program LWEIGHT (v3) has been used to calculate the weighted mean of the chosen experimental values which yields a mean of 14.82 d and an internal uncertainty of *0.19 d* with reduced chi-square of 0.14.

3. α Particles

The energies of the α-particle transitions have been calculated from the Q_α (2003Au03) and level energies. The level energies of ^{225}Ra as deduced in 2009Ja03 has been adopted. The adopted values of the level energies, their spin and parities, the half-lives of the levels (wherever available), the energies and the probabilities of the alpha transitions are given in Table-3 below. The alpha particle energies and the absolute probabilities (per 100 decays) are evaluated values from 2009Ja03.

Table-3: Levels of ^{225}Ra populated by α-decay of ^{229}Th

Level	Level Energy (keV)	Spin & Parity	Half-life	Energy of α-particle (keV)	Probability of α-transition (%)
0	0.	$1/2^+$	14.8 (2) d	5078 (2)	0.05
1	25.41 (2)	$5/2^+$	0.88 (4) ns	5053 (2)	6.5 (1)
2	31.56 (3)	$3/2^-$	2.1 (5) ns	5047 (2)	< 0.2
3	42.77 (3)	$3/2^+$	< 3 ns	5036 (2)	0.23 (2)
4	55.16 (6)	$(1/2^-)$		5023 (2)	0.009 (3)
5	69.36 (6)	$(7/2^-)$		5009 (2)	0.09 (1)
6	100.5 (6)	$9/2^+$		4978.5 (12)	3.23 (4)
7	101.72	$(3/2^+)$			
8	111.6 (5)	$7/2^+$		4967.5 (12)	5.91 (6)
9	120.36 (6)	$5/2^-$			
10	149.96 (6)	$3/2^+$		4930 (2)	0.16 (5)
11	159.59				
12	179.75 (2)	$5/2^+$		4901.0 (12)	10.09 (8)
13	203.47	$(9/2^-)$		~4878	~0.03
14	216.28			~4865	~0.03
15	220.55 (7)	$(7/2^+,9/2^+)$		4861 (2)	0.27 (10)
16	225.08				
17	226.9 (3)	$(11/2^+)$		~4852	~0.03
18	236.25 (2)	$5/2^+$		4845.3 (12)	55.6 (2)
19	243.56 (4)	$7/2^+$		4838 (2)	4.9 (2)
20	248.63			~4833	~0.28
21	260.18	$(5/2)^-$			
22	267.92 (5)	$7/2^+$		4814.6 (12)	9.20 (8)
23	272.15 (15)			~4809	~0.21
24	284.49 (5)	$7/2^+$		4797.8 (12)	1.5 (2)
25	292.72				
26	321.76 (8)	$(9/2^+)$		4761 (2)	1.0 (4)
27	327.71			~4754	~0.05
28	335.4			~4748	~0.005
29	349.43			~4737	~0.01
30	390.21	$(11/2^+)$		4694 (2)	0.12 (2)
31	394.24				
32	394.45	$(5/2)^+$			
33	394.72 (13)	$(3/2,5/2,7/2)^+$		4690 (2)	0.22 (8)
34	399.54				
35	403.5				
36	416.77			~4667	~0.001
37	446.45				
38	478.1			4608 (2)	0.050 (8)
39	486.82	$(5/2^+)$			
40	487.22 (3)	$(13/2^+)$		4599 (3)	0.02 (1)
41	535.25	$(5/2^+)$			
42	592.79				
43	604.51			4484 (2)	0.03 (2)
44	608.93			4478 (3)	~0.005

The alpha particle energies have been deduced from the alpha transition energies taking in to account the recoil energy for ^{225}Ra. The deduced values of the alpha particle energies along with the values from the 1987He28 and 1970Ba20 are given in Table 4.

Table-4: Energy and probability of α-particles from the decay of ^{229}Th

Level	Level Energy (keV)	Energy of α-particle (keV)			Probability of α-transition (%)		
		Deduced	1987He28	1970Ba20	Adopted	1987He28	1970Ba20
0	0.	5077.3 (10)	5077 (2)	5077	0.05	0.05	0.01
1	25.41 (2)	5052.4 (10)	5053 (2)	5052	6.5 (1)	6.6 (1)	1.6
2	31.56 (3)	5046.3 (10)		5050	< 0.2		5.2
3	42.77 (3)	5035.3 (10)	5036 (2)	5033	0.23 (2)	0.24 (2)	0.24
4	55.16 (6)	5023.1 (10)	5023 (2)		0.009 (3)	0.009 (3)	
5	69.36 (6)	5009.1 (10)	5009 (2)		0.09 (1)	0.09 (1)	
6	100.5 (6)	4978.6 (10)	4979 (2)	4977.9 (12)	3.23 (4)	3.4 (1)	3.2
7	101.72						
8	111.6 (5)	4967.7 (10)	4968 (2)	4966.9 (12)	5.91 (6)	7.0 (1)	6.4
9	120.36 (6)						
10	149.96 (6)	4929.9 (10)	4930 (2)	4929	0.16 (5)	0.21 (2)	0.11
11	159.59						
12	179.75 (2)	4900.7 (10)	4901 (2)	4900.4 (12)	10.09 (8)	10.6 (2)	10.8
13	203.47	4877.4 (10)		~4878	~0.03		~0.03
14	216.28	4864.8 (10)		~4865	~0.03		~0.03
15	220.55 (7)	4860.7 (10)	4860 (2)	~4861	0.27 (10)	0.38 (4)	0.18
16	225.08						
17	226.9 (3)	4854.4 (10)		~4852	~0.03		~0.03
18	236.25 (2)	4845.2 (10)	4845 (2)	4844.7 (12)	55.6 (2)	53.0	56.2
19	243.56 (4)	4838.0 (10)	4838 (2)	~4837	4.9 (2)	5.2	4.8
20	248.63	4833.1 (10)		~4833	~0.28		~0.29
21	260.18						
22	267.92 (5)	4814.1 (10)	4815 (2)	4814.0 (12)	9.20 (8)	9.6 (2)	8.4
23	272.15 (15)	4810.0 (10)		~4809	~0.21		~0.22
24	284.49 (5)	4797.8 (10)	4798 (2)	4797.2 (12)	1.5 (2)	1.70 (5)	1.27
25	292.72						
26	321.76 (8)	4761.2 (10)	4760 (2)	4761	1.0 (4)	1.40 (4)	0.63
27	327.71	4755.4 (10)		~4754	~0.05		~0.05
28	335.4	4747.8 (10)		~4748	~0.005		~0.005
29	349.43	4734.0 (10)		~4737	~0.01		~0.01
30	390.21	4693.9 (10)	4695 (2)	4692	0.12 (2)	0.14 (2)	~0.08
31	394.24						
32	394.45						
33	394.72 (13)	4689.5 (10)	4690 (2)	~4688	0.22 (8)	0.31 (2)	0.15
34	399.54						
35	403.5						
36	416.77	4667.8 (10)		~4667	~0.001		~0.001
37	446.45						
38	478.1	4607.6 (10)	4608 (2)		0.050 (8)	0.050 (8)	
39	486.82						
40	487.22 (3)	4598.6 (10)	4600 (2)	4598	0.02 (1)	0.029 (5)	~0.007
41	535.25						
42	592.79						
43	604.51	4483.4 (10)	4484 (2)	4484	0.03 (2)	0.050 (7)	~0.009
44	608.93	4479.1 (10)		4478	~0.005		~0.005

4. γ Transitions

The gamma-ray transitions in ^{229}Th following the ^{233}U decay is presented in section 2.2 along with the multipolarity of the gamma rays and the internal conversion coefficients. The recommended γ-ray energies and absolute emission probabilities are from the evaluated values in 2009Ja03 which uses mostly the values reported in 1987He28 and 2000Ga52. The energies and intensities of the gamma rays in ^{225}Ra produced by the α-decay of ^{229}Th are given in Table-5 and Table-6 from different measurements.

Table-5: Energy of γ-rays in ^{225}Ra from the decay of ^{229}Th

	2000Ga52	1987He28	1983Ra01	1981Di14
$\gamma_{8,6}$	11.1 (1)	11.1		
$\gamma_{43,42}$	11.79 (20)			
$\gamma_{3,1}$	17.25 (10)	17.36 (3)		
a	19.08 (20)			
a	21.60 (10)	21.58 (2)		
$\gamma_{4,2}$		23.6		
$\gamma_{1,0}$	25.42 (10)	25.39 (2)		
a		27.50 (2)		
$\gamma_{23,19}$	28.68 (10)	30.3	28.50 (14)	
$\gamma_{10,9}$	29.9 (1)			
$\gamma_{6,5}$	31.43 (10)	31.10 (5)	31.13 (3)	31.24
$\gamma_{2,0}$		31.50 (5)	31.53 (4)	
$\gamma_{22,18}$		31.57 (9)		
$\gamma_{25,21}$	33.04 (20)			
a	34.02 (20)			
$\gamma_{5,2}$	37.78 (20)	37.8 (1)		
$\gamma_{8,5}$	42.24 (10)	42.3 (1)		
$\gamma_{3,0}$	42.77 (10)	42.82 (5)	42.63 (2)	42.79
$\gamma_{5,1}$	43.99 (5)	43.990 (10)	43.96 (2)	
$\gamma_{22,15}$	46.52 (10)	46.52 (4)		
$\gamma_{26,23}$	49.74 (10)	49.75 (8)		
$\gamma_{9,5}$	50.98 (10)	50.99 (4)		
a		53.2 (1)		
$\gamma_{26,22}$	53.84 (10)	53.75 (20)	53.84 (9)	
$\gamma_{4,0}$	55.20 (10)	55.11 (3)		
$\gamma_{18,12}$	56.52 (5)	56.518 (5)	56.50 (3)	56.57
$\gamma_{12,9}$	59.33 (10)			
$\gamma_{24,15}$	63.7	63.7 (2)		
$\gamma_{9,4}$	64.96 (10)			
$\gamma_{25,17}$	65.91 (10)			
$\gamma_{12,8}$	68.1 (1)	68.09 (4)	68.05 (8)	
$\gamma_{30,26}$	68.2			
$\gamma_{15,11}$	68.80 (10)		68.80 (7)	
$\gamma_{8,3}$		68.83 (1)		
$\gamma_{33,26}$	72.81 (10)	72.739 (10)		
$\gamma_{6,1}$		75.10 (10)	75.10 (5)	
$\gamma_{16,10}$	75.19 (10)			
a		75.3 (1)		
a	76.67 (20)			
$\gamma_{9,3}$	77.60 (10)	77.63 (5)		

	2000Ga52	1987He28	1983Ra01	1981Di14
$\gamma_{26,19}$	78.53 (10)	78.3 (2)		
$\gamma_{8,1}$	86.33 (4)	86.25 (4)		
$\gamma_{18,10}$		86.40 (5)	86.35 (4)	86.38
$\gamma_{9,2}$	89.09 (20)			
$\gamma_{29,21}$	89.09 (20)			
$\gamma_{26,17}$	94.70 (10)			
$\gamma_{10,4}$		94.73 (2)	94.72 (2)	
$\gamma_{9,1}$		94.92 (8)		
$\gamma_{40,30}$	97.01 (12)			
$\gamma_{20,10}$	98.86 (10)			
$\gamma_{26,15}$	100.8 (2)	101.1 (2)		
$\gamma_{7,0}$	101.58 (10)			
$\gamma_{27,16}$	102.54 (2)		103.71 (3)	
$\gamma_{24,12}$	104.32 (10)	104.6 (2)		
$\gamma_{10,3}$	107.11 (10)	107.108 (8)	107.15 (2)	107.20
$\gamma_{15,8}$	109.10 (10)	109.2	109.21 (6)	
$\gamma_{12,5}$	110.33 (5)	110.332 (8)	110.38 (3)	
$\gamma_{42,38}$	114.75 (10)	115.3 (4)		
$\gamma_{14,6}$	115.85 (10)	115.98 (10)		
$\gamma_{10,2}$	118.10 (10)	117.99 (15)	118.21 (9)	
$\gamma_{15,6}$	120.08 (5)	119.98 (2)	120.16 (8)	
$\gamma_{19,9}$	123.21 (2)	123.193 (13)	123.19 (3)	
$\gamma_{10,1}$	124.58 (5)	124.55 (5)	124.59 (2)	124.68
$\gamma_{18,8}$		124.65 (5)		
$\gamma_{11,0}$	126.06 (20)	126.4 (2)		
$\gamma_{17,6}$	126.48 (10)	126.5 (3)	126.76 (9)	
[a]		129.04 (3)		
$\gamma_{19,8}$	131.89 (5)	131.926 (5)		132.00
[a]		132.6 (1)		
$\gamma_{13,5}$	134.19 (10)	134.2 (1)	134.33 (8)	
[a]		135.71 (7)		
$\gamma_{12,3}$	136.97 (5)	136.990 (4)	136.99 (3)	137.06
$\gamma_{20,8}$	137.0 (1)			
$\gamma_{21,9}$	139.8 (1)	140.3 (2)		
$\gamma_{26,12}$		142.0 (1)		
$\gamma_{19,6}$	142.94 (5)	142.962 (5)	142.97 (3)	143.05
[a]		146.8		
$\gamma_{22,9}$	147.65 (5)	147.64 (5)	147.66 (3)	
$\gamma_{12,2}$	148.15 (5)	148.15 (4)	148.17 (3)	148.18
$\gamma_{10,0}$	149.89 (10)	150.04 (2)	149.91 (4)	
$\gamma_{33,19}$	151.6 (3)	151.6 (3)		
$\gamma_{12,1}$	154.34 (5)	154.336 (10)	154.37 (2)	154.36
$\gamma_{22,8}$	156.38 (5)	156.409 (9)	156.41 (2)	156.45
$\gamma_{33,18}$	158.35 (10)	158.42 (12)	158.42 (4)	
$\gamma_{23,8}$		160.6	160.48 (56)	
$\gamma_{30,17}$	163.15 (20)	163.34 (17)		
$\gamma_{18,5}$	166.92 (5)	166.976 (7)		
$\gamma_{22,6}$	167.49 (10)	167.45 (5)	167.14 (4)	
$\gamma_{30,15}$	169.2 (3)	169.09 (3)		
[a]		171.5 (2)		
$\gamma_{23,6}$	171.76 (5)	171.75 (2)	171.59 (7)	

	2000Ga52	1987He28	1983Ra01	1981Di14
$\gamma_{24,8}$	172.91 (10)	172.926 (18)	172.91 (4)	173.01
$\gamma_{33,15}$	174.05 (11)	174.22 (11)		
$\gamma_{37,23}$	174.7 (2)			
$\gamma_{12,0}$	179.76 (5)	179.757 (7)	179.75 (3)	179.85
$\gamma_{16,3}$	182.12 (10)			
$\gamma_{35,15}$	183.0 (1)			
$\gamma_{24,6}$	183.93 (10)	183.928 (8)	183.95 (3)	184.0
$\gamma_{28,10}$	185.6 (1)			
$\gamma_{37,21}$	186.1 (1)			
$\gamma_{42,35}$	189.25 (6)			
$\gamma_{21,5}$	190.63 (20)	190.2 (2)		
$\gamma_{16,2}$	193.52 (5)			
$\gamma_{18,3}$	193.52 (5)	193.509 (5)	193.53 (2)	193.59
$\gamma_{15,1}$	194.94 (20)	194.3 (3)		
$\gamma_{19,3}$	200.80 (10)	200.807 (16)	200.81 (3)	
$\gamma_{18,2}$	204.69 (5)	204.690 (5)	204.70 (2)	204.74
$\gamma_{26,8}$	210.32 (5)	210.15 (8)	210.31 (5)	
$\gamma_{18,1}$	210.89 (3)	210.853 (3)	210.90 (5)	210.93
[a]	211.47 (10)			
$\gamma_{41,26}$	213.48 (5)			
$\gamma_{24,5}$	215.13 (10)	215.100 (10)	215.16 (8)	
$\gamma_{27,8}$	216.0 (1)			
$\gamma_{21,3}$	217.41 (10)			
$\gamma_{19,1}$	218.15 (5)	218.154 (17)	218.15 (4)	
$\gamma_{34,12}$	219.8 (1)			
$\gamma_{26,6}$	221.23 (10)	221.22 (5)	221.31 (9)	
$\gamma_{16,0}$	225.26 (10)	225.149 (19)	225.25 (6)	
$\gamma_{21,2}$	228.6 (1)			
$\gamma_{21,1}$	234.8 (1)			
$\gamma_{18,0}$	236.29 (5)	236.249 (8)	236.31 (6)	
$\gamma_{22,1}$	242.6 (2)	242.269 (14)	242.61 (7)	
$\gamma_{31,10}$	244.4 (1)			
$\gamma_{25,3}$	250.1 (1)			
$\gamma_{26,5}$	252.44 (5)	252.43 (3)	252.49 (5)	
$\gamma_{24,1}$	259.05 (10)	259.08 (4)	259.15 (5)	
$\gamma_{25,1}$	267.4 (1)			
$\gamma_{33,9}$	274.1 (1)			
$\gamma_{43,27}$	276.85 (10)			
$\gamma_{30,8}$	278.65 (5)			
$\gamma_{44,27}$	281.27 (10)			
$\gamma_{33,8}$	282.6 (1)			
$\gamma_{30,6}$	289.62 (5)	289.50 (16)		
[a]	292.27 (5)			
$\gamma_{33,6}$	293.78 (10)			
$\gamma_{26,1}$	296.21 (10)	296.2 (2)		
$\gamma_{38,12}$	298.72 (12)			
$\gamma_{28,2}$	303.75 (10)			
$\gamma_{39,12}$	307.3 (1)			
$\gamma_{28,1}$	310.1 (1)			
$\gamma_{45,29}$	313.3 (1)			
$\gamma_{29,2}$	317.8 (1)			

	2000Ga52	1987He28	1983Ra01	1981Di14
$\gamma_{42,23}$	320.8 (1)			
$\gamma_{31,5}$	324.6 (1)			
$\gamma_{27,0}$	327.9 (1)			
$\gamma_{38,10}$	328.2 (1)			
$\gamma_{34,5}$	329.9 (2)			
$\gamma_{37,8}$	334.74 (10)			
$\gamma_{43,22}$	336.7 (1)			
$\gamma_{45,26}$	341.1 (1)			
$\gamma_{34,4}$	344.3 (3)			
$\gamma_{36,5}$	347.4 (4)			
$\gamma_{29,0}$	349.4 (4)			
$\gamma_{32,3}$	351.7 (1)			
$\gamma_{38,9}$	358.0 (1)			
$\gamma_{43,19}$	361.0 (1)			
$\gamma_{38,8}$	366.5 (1)			
$\gamma_{43,18}$	368.1 (1)			
$\gamma_{31,1}$	368.9 (1)			
$\gamma_{39,8}$	375.1 (1)			
$\gamma_{38,6}$	377.4 (4)			
$\gamma_{43,16}$	379.4 (1)			
$\gamma_{39,6}$	386.4 (1)			
$\gamma_{32,0}$	395.3 (2)			
$\gamma_{34,0}$	399.9 (2)			
$\gamma_{35,0}$	403.3 (1)			
$\gamma_{38,5}$	408.5 (1)			
$\gamma_{41,9}$	414.61 (10)			
$\gamma_{39,5}$	417.4 (1)			
$\gamma_{45,19}$	419.9 (2)			
[a]	422.8 (1)			
$\gamma_{43,12}$	424.8 (1)			
$\gamma_{38,3}$	435.3 (1)			
$\gamma_{39,3}$	444.1 (1)			
$\gamma_{38,1}$	452.6 (1)			
$\gamma_{43,10}$	454.76 (10)			
[a]	455.85 (10)			
$\gamma_{44,10}$	459.1 (3)			
$\gamma_{39,1}$	461.4 (1)			
$\gamma_{41,5}$	465 (1)			
$\gamma_{38,0}$	478.0 (1)			
$\gamma_{45,12}$	483.7 (1)			
$\gamma_{39,0}$	487.3 (2)			
$\gamma_{43,8}$	492.9 (1)			
$\gamma_{41,2}$	503.6 (1)			
$\gamma_{45,10}$	513.5 (2)			
$\gamma_{42,5}$	523.5 (1)			
$\gamma_{41,0}$	535.1 (1)			
$\gamma_{45,9}$	543.0 (3)			
$\gamma_{42,3}$	549.8 (5)			
$\gamma_{45,8}$	551.7 (2)			
$\gamma_{43,3}$	561.8 (1)			
$\gamma_{44,3}$	565.7 (3)			

	2000Ga52	1987He28	1983Ra01	1981Di14
$\gamma_{43,2}$	573.0 (1)			
$\gamma_{43,1}$	579.2 (2)			
$\gamma_{42,0}$	592.5 (1)			
$\gamma_{45,5}$	594.4 (3)			
[a]	603.6 (2)			

[a] unplaced gamma rays.

γ-ray intensity normalization: Absolute γ intensities were measured by 1986He06 with absolutely calibrated Ge(Li) detector. Normalization of relative photon intensities to I(193γ) = 4.41 (6) %, as measured by 1986He06, yields Iγ normalization = 1.026 (14). Other absolute γ intensity determinations: I(193γ) = 4.5 % (1970Tr04), 5.89 (18) % (1981Di14), 3.77 (8) % (1983Ra01). The value of Pγ+ce for the 11.1 keV (8,6) transition was deduced by 1987He28 from γγ coincidence data where 11.1γ is an unobserved transition. The value of $P\gamma_{8,6}$ (11.1 keV) has been obtained by considering a M1+E2 transition from the decay scheme.

Table-6: Intensity of γ-rays in ^{225}Ra from the decay of ^{229}Th

	2000Ga52[b]	1987He28[b]	1986He06	1983Ra01	1981Di14
$\gamma_{8,6}$	12 (2)[c]				
$\gamma_{43,42}$	~0.0005				
$\gamma_{3,1}$	0.22 (10)				
[a]	0.22 (3)				
[a]	0.08 (2)	0.007 (10)			
$\gamma_{4,2}$		0.0012 (1)			
$\gamma_{1,0}$	0.011 (2)				
[a]		0.034 (17)			
$\gamma_{23,19}$	0.10 (3)			0.117 (24)	
$\gamma_{10,9}$	0.11 (2)	0.038 (13)			
$\gamma_{6,5}$	0.62 (8)	0.82 (8)		0.896 (80)	1.43 (5)
$\gamma_{2,0}$	1.86 (20)	1.16 (8)	2.45 (6)	1.692 (85)	
$\gamma_{22,18}$	0.022 (10)	0.066 (10)			
$\gamma_{25,21}$	~0.01				
[a]	~0.01				
$\gamma_{5,2}$	0.0030 (2)				
$\gamma_{8,5}$	0.077 (8)	0.080 (8)	0.199 (6)		
$\gamma_{3,0}$	0.17 (2)	0.16 (1)		0.188 (10)	0.272 (11)
$\gamma_{5,1}$	0.67 (7)	0.64 (3)	0.762 (17)	0.604 (20)	
$\gamma_{22,15}$	0.0009 (2)	0.020 (2)			
$\gamma_{26,23}$	0.0107 (17)	0.021 (2)			
$\gamma_{9,5}$	0.0108 (16)	0.017 (4)			
$\gamma_{26,22}$	0.020 (3)	0.011 (3)		0.017 (3)	
$\gamma_{4,0}$	0.015 (3)	0.0026 (4)			
$\gamma_{18,12}$	0.33 (3)	0.28 (2)	0.312 (7)	0.246 (6)	0.427 (15)
$\gamma_{12,9}$	0.012 (2)				
$\gamma_{9,4}$	0.085 (11)				
$\gamma_{25,17}$	0.157 (17)				
$\gamma_{12,8}$		0.067 (10)		0.052 (14)	
$\gamma_{15,11}$	0.12 (3)			0.060 (13)	

	2000Ga52[b]	1987He28[b]	1986He06	1983Ra01	1981Di14
$\gamma_{8,3}$		0.133 (13)			
$\gamma_{33,26}$	0.012 (3)	0.14 (2)			
$\gamma_{6,1}$		0.59 (13)		0.420 (43)	
$\gamma_{16,10}$	0.52 (5)				
[a]	0.035 (8)				
$\gamma_{9,3}$	0.054 (6)	0.044 (6)			
$\gamma_{26,19}$	0.044 (5)	0.008 (2)			
$\gamma_{8,1}$	0.7 (2)	1.3 (2)			
$\gamma_{18,10}$	3.2 (4)	2.5 (1)		2.732 (74)	2.94 (9)
$\gamma_{9,2}$	~0.14				
$\gamma_{29,21}$	~0.01				
$\gamma_{26,17}$	0.26 (2)				
$\gamma_{10,4}$		0.26 (2)	0.465 (8)	0.232 (6)	
$\gamma_{9,1}$		0.013 (3)			
$\gamma_{40,30}$	0.011 (3)				
$\gamma_{20,10}$	0.117 (15)				
$\gamma_{26,15}$	0.018 (3)	0.018 (3)			
$\gamma_{7,0}$	0.048 (7)				
$\gamma_{27,16}$	0.156 (19)			0.451 (35)	
$\gamma_{24,12}$	0.038 (7)	0.009 (3)			
$\gamma_{10,3}$	0.85 (8)	0.79 (4)	0.809 (13)	0.656 (9)	0.95 (3)
$\gamma_{15,8}$	0.029 (3)	0.043 (8)		0.023 (4)	
$\gamma_{12,5}$	0.121 (12)	0.121 (12)	0.128 (3)	0.107 (4)	
$\gamma_{42,38}$	0.0147 (22)	0.027 (4)			
$\gamma_{14,6}$	0.010 (3)	0.017 (3)			
$\gamma_{10,2}$	0.013 (4)	0.013 (4)		0.015 (5)	
$\gamma_{15,6}$	0.034 (4)	0.05 (2)		0.017 (3)	
$\gamma_{19,9}$	0.155 (16)	0.147 (7)	0.197 (3)	0.120 (4)	
$\gamma_{10,1}$	0.78 (6)	0.67 (6)	1.449 (20)	1.040 (12)	1.62 (5)
$\gamma_{18,8}$	0.66 (6)	0.72 (6)			
$\gamma_{11,0}$	0.0298 (10)	0.02 (1)			
$\gamma_{17,6}$	0.014 (4)	0.011 (5)		0.013 (4)	
[a]		0.016 (10)			
$\gamma_{19,8}$	0.38 (4)	0.327 (12)	0.327 (5)		0.433 (15)
$\gamma_{13,5}$	0.015 (4)	0.012 (3)		0.015 (3)	
$\gamma_{12,3}$	1.21 (12)	1.15 (3)	1.171 (16)	0.904 (18)	1.51 (5)
$\gamma_{20,8}$	0.04 (1)				
$\gamma_{21,9}$	0.0045 (10)				
$\gamma_{26,12}$		0.011 (3)			
$\gamma_{19,6}$	0.40 (4)	0.394 (12)	0.401 (6)	0.314 (6)	0.532 (19)
[a]		0.016 (8)			
$\gamma_{22,9}$	0.23 (2)	0.20 (2)	1.091 (15)	0.183 (14)	
$\gamma_{12,2}$	0.87 (9)	0.86 (6)		0.708 (17)	1.26 (4)
$\gamma_{10,0}$	0.053 (6)	<0.06		0.0042 (3)	
$\gamma_{33,19}$	~0.025				
$\gamma_{12,1}$	0.73 (7)	0.75 (2)	0.922 (13)[d]	0.612 (12)	1.13 (4)
$\gamma_{22,8}$	1.16 (11)	1.16 (3)	1.237 (18)	0.972 (18)	1.26 (4)

	2000Ga52[b]	1987He28[b]	1986He06	1983Ra01	1981Di14
$\gamma_{33,18}$	0.040 (4)	0.047 (5)		0.034 (3)	
$\gamma_{23,8}$				0.005 (3)	
$\gamma_{30,17}$	0.0161 (21)	0.020 (7)			
$\gamma_{18,5}$	0.222 (22)	0.200 (10)			
$\gamma_{22,6}$	0.04 (1)	0.05 (1)		0.113 (10)	
$\gamma_{16,4}$	0.0039 (14)				
[a]		0.018 (5)			
$\gamma_{23,6}$	0.039 (4)	<0.04		0.020 (5)	
$\gamma_{24,8}$	0.123 (12)	0.11 (1)		0.093 (6)	0.130 (6)
$\gamma_{33,15}$	0.0065 (18)	0.009 (5)			
$\gamma_{37,23}$	0.030 (3)				
$\gamma_{12,0}$	0.196 (20)	0.192 (15)	0.215 (4)	0.176 (5)	0.262 (10)
$\gamma_{16,3}$	0.0054 (11)				
$\gamma_{35,15}$	0.0069 (12)				
$\gamma_{24,6}$	0.147 (15)	0.138 (7)		0.118 (6)	0.091 (9)
$\gamma_{28,10}$	<0.002				
$\gamma_{37,21}$	0.013 (5)				
$\gamma_{42,35}$	0.0101 (21)				
$\gamma_{21,5}$	0.0098 (20)				
$\gamma_{16,2}$	0.0007 (3)				
$\gamma_{18,3}$	4.3	4.3	4.41 (6)	3.769 (75)	5.89 (18)
$\gamma_{15,1}$	0.0162 (23)	0.03 (2)			
$\gamma_{19,3}$	0.073 (8)	0.067 (3)		0.066 (5)	
$\gamma_{18,2}$	0.57 (4)	0.58 (3)	0.595 (9)	0.495 (12)	0.75 (4)
$\gamma_{26,8}$	0.26 (3)	0.19 (4)	3.18 (4)	0.210 (33)	
$\gamma_{18,1}$	2.77 (3)	2.7 (3)		2.467 (63)	4.00 (13)
[a]	0.044 (12)				
$\gamma_{41,26}$	0.0085 (16)				
$\gamma_{24,5}$	0.145 (14)	0.134 (10)		0.146 (16)	
$\gamma_{27,8}$	0.052 (6)				
$\gamma_{21,3}$	0.0063 (11)				
$\gamma_{19,1}$	0.134 (12)	0.18 (2)		0.149 (37)	
$\gamma_{34,12}$	0.0033 (8)				
$\gamma_{26,6}$	0.024 (2)	0.022 (6)		0.022 (3)	
$\gamma_{16,0}$	0.061 (6)	0.070 (10)		0.048 (4)	
$\gamma_{21,2}$	0.0006 (2)				
$\gamma_{21,1}$	0.0008 (2)				
$\gamma_{18,0}$	0.174 (15)	0.170 (9)		0.158 (28)	
$\gamma_{22,1}$	0.081 (8)	0.092 (14)		0.065 (7)	
$\gamma_{31,10}$	0.00127 (32)				
$\gamma_{25,3}$	0.00033 (16)				
$\gamma_{26,5}$	0.093 (9)	0.093 (12)		0.089 (5)	
$\gamma_{24,1}$	0.023 (5)	0.033 (5)		0.033 (11)	
$\gamma_{25,1}$	0.0008 (3)				
$\gamma_{33,9}$	0.0007 (2)				
$\gamma_{43,27}$	0.0041 (10)				
$\gamma_{30,8}$	0.0066 (8)				

	2000Ga52[b]	1987He28[b]	1986He06	1983Ra01	1981Di14
$\gamma_{44,27}$	0.007 (1)				
$\gamma_{33,8}$	0.0037 (7)				
$\gamma_{30,6}$	0.0146 (17)	0.006 (4)			
a	0.0055 (8)				
$\gamma_{33,6}$	0.0064 (8)				
$\gamma_{26,1}$	0.0161 (17)	0.012 (10)			
$\gamma_{38,12}$	0.0068 (8)				
$\gamma_{28,2}$	0.0017 (3)				
$\gamma_{39,12}$	0.006 (3)				
$\gamma_{28,1}$	0.00199 (28)				
$\gamma_{45,29}$	0.00036 (11)				
$\gamma_{29,2}$	0.00053 (14)				
$\gamma_{42,23}$	0.00016 (7)				
$\gamma_{31,5}$	0.00042 (13)				
$\gamma_{27,0}$	0.016 (3)				
$\gamma_{38,10}$	0.0020 (8)				
$\gamma_{34,5}$	0.0006 (2)				
$\gamma_{37,8}$	0.00042 (11)				
$\gamma_{43,22}$	0.0080 (1)				
$\gamma_{45,26}$	0.0008 (2)				
$\gamma_{34,4}$	<0.0001				
$\gamma_{36,5}$	0.0006 (1)				
$\gamma_{29,0}$	0.0004 (1)				
$\gamma_{32,3}$	0.0005 (1)				
$\gamma_{38,9}$	0.006 (1)				
$\gamma_{43,19}$	0.0006 (1)				
$\gamma_{38,8}$	0.0004 (1)				
$\gamma_{43,18}$	0.0019 (3)				
$\gamma_{31,1}$	0.0019 (3)				
$\gamma_{39,8}$	0.0003 (1)				
$\gamma_{38,6}$	0.0028 (3)				
$\gamma_{43,16}$	0.0013 (2)				
$\gamma_{39,6}$	0.0008 (2)				
$\gamma_{32,0}$	0.0008 (1)				
$\gamma_{34,0}$	0.00014 (6)				
$\gamma_{35,0}$	0.0018 (2)				
$\gamma_{38,5}$	0.0010 (1)				
$\gamma_{41,9}$	0.0003 (1)				
$\gamma_{39,5}$	0.0014 (2)				
$\gamma_{45,19}$	0.0006 (1)				
a	0.0005 (1)				
$\gamma_{43,12}$	0.0032 (3)				
$\gamma_{38,3}$	0.0031 (4)				
$\gamma_{39,3}$	0.0005 (1)				
$\gamma_{38,1}$	0.0017 (2)				
$\gamma_{43,10}$	0.0102 (11)				
a	0.0114 (14)				

	2000Ga52[b]	1987He28[b]	1986He06	1983Ra01	1981Di14
$\gamma_{44,10}$	~0.001				
$\gamma_{39,1}$	0.0076 (8)				
$\gamma_{41,5}$	~0.0001				
$\gamma_{38,0}$	0.0036 (4)				
$\gamma_{45,12}$	0.0018 (2)				
$\gamma_{39,0}$	0.0004 (1)				
$\gamma_{43,8}$	0.00148 (16)				
$\gamma_{41,2}$	0.00012 (5)				
$\gamma_{45,10}$	0.0007 (2)				
$\gamma_{42,5}$	0.0005 (1)				
$\gamma_{41,0}$	0.0013 (2)				
$\gamma_{45,9}$	~0.0001				
$\gamma_{42,3}$	~0.0001				
$\gamma_{45,8}$	0.00011 (4)				
$\gamma_{43,3}$	0.0019 (2)				
$\gamma_{44,3}$	0.0009 (1)				
$\gamma_{43,2}$	0.0027 (3)				
$\gamma_{43,1}$	0.0006 (1)				
$\gamma_{42,0}$	0.0003 (1)				
$\gamma_{45,5}$	~0.0001				
[a]	0.0009 (2)				

[a] unplaced gamma rays
[b] For absolute intensity per 100 decays multiply by 1.026 (14)
[c] Total transition intensity $I_{\gamma+ce}$
[d] value includes contribution from daughter activity.

5. Atomic Data

The Atomic data of Fluorescence yields were obtained from 1996Sc06. The energies of the K-Auger electrons were obtained from the reference 1998ScZM while the energies of and the yield of Ra X-rays were obtained from 1999ScZX.The X-ray and Auger electron emission probabilities have been calculated by using the computer program EMISSION (V3.10, 28-Jan-2003) described in 2000Sc47. The energies of the internal conversion electrons have been calculated using the electron binding energies from 1977La19 and 1996FIZX. Absolute conversion electron emission probabilities have been calculated by using the conversion coefficient of the γ-rays and their absolute emission probabilities.

5.1 Electron Emission

The energies of the conversion electrons have been obtained from the gamma transition energies and the electron binding energies. The emission probabilities of conversion electrons have been deduced from the evaluated P(γ) and ICC values. The number of K- and L- Auger electrons per 100 disintegrations has been deduced using the evaluated XK- and XL- emission probabilities.

5.2 X-ray Emission

The calculated X-rays' emission probabilities have been compared with the ones measured by 1983Ra01 and 1987He28 in Table 7.

Table 7: Comparison of calculated and measured intensities of Ra X-rays

<table>
<tr><th></th><th>X-ray Energy (keV)</th><th>1983Ra01</th><th>1987He28</th><th>Deduced</th></tr>
<tr><td>XL</td><td>10.62 – 18.41</td><td>78.922[a]</td><td></td><td>106 (7)</td></tr>
<tr><td>XKα_2</td><td>85.43</td><td>9.820 (17)</td><td rowspan="8">49.3 (20)</td><td>14.3 (6)</td></tr>
<tr><td>XKα_1</td><td>88.47</td><td>16.681 (251)</td><td>23.4 (9)</td></tr>
<tr><td>XKβ_3</td><td>99.432</td><td>2.245 (70)</td><td rowspan="3">8.2 (4)</td></tr>
<tr><td>XKβ_1</td><td>100.13</td><td>3.927 (86)</td></tr>
<tr><td>XK$\beta_5^{//}$</td><td>100.738</td><td></td></tr>
<tr><td>XKβ_2</td><td>102.89</td><td>1.443 (46)</td><td rowspan="3">2.69 (12)</td></tr>
<tr><td>XKβ_4</td><td>103.295</td><td></td></tr>
<tr><td>XKO$_{2,3}$</td><td>103.74</td><td></td></tr>
</table>

[a] The intensity does not include the LX-rays below 12.3 keV.

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