^{221}Fr - Comments on evaluation of decay data
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This evaluation was completed in 2007. Literature available by December 2007 was included.

1 Decay Scheme

^{221}Fr disintegrates 99.9952 (15) % by α emission to levels in ^{217}At and 0.0048 (15) % by β^- emission to levels in ^{221}Ra. ^{221}Fr ground state has $J^\pi = 5/2^-$ (2003Ak06).

The α decay scheme of ^{221}Fr was built based on the measurement described in 1995Sh01, 1999Gr33 and 2002Gr36. A study of 1997Ch53 showed the existence of a possible weak ß$^-$ decay of $(4.8 \pm 1.5)\ 10^{-3}$ % to ^{221}Ra. The β^- decay scheme of ^{221}Fr has not been studied.

The recommended Q(a) value of 6457.8 (14) keV in Audi(2003Au03) agrees with the Q(a) value of 6461.5 (25) keV, calculated by the evaluator (using program RADLST) from average radiation energies. This agreement supports the completeness and correctness of the decay scheme.

2 Nuclear Data

The Q value is from the 2003Au03 evaluation.

Level energies, have been obtained from a least-squares fit to γ-ray energies (GTOL computer code). Spin and parities are from 2003Ak06.

The measured and our evaluated ^{221}Fr half-life values are listed in Table 1. Notice that uncertainties in tables referred to the least significant digits.

Table 1 - Measured half-life values of ^{221}Fr and recommended value, in minutes

$T_{1/2}$ (min)	References	measurement method
5	1947En03	
4.8	1950Ha52	Alpha pulse analyzer
4.9 (2)	1967LoZZ	
4.79 (2)	2007Je07	From Si sample. Metallic samples(Au,W) give shorter value
4.9 (2)	2003Ak06	NDS, from 1967LoZZ
4.85 (6)		Unweighted mean of 1967LoZZ and 2007Je07
4.791 (20)		Weighted mean of 1967LoZZ and 2007Je07,χ^2=0.3
4.79 (2)	2007	Recommended value, from 2007Je07

2007Je07 measured the half-life at room temperature in different materials and obtained an improved value. As the weighted mean of 4.9 (2) min (1967LoZZ) and 4.79 (2) min (2007Je07) is very close to this most precise measurement, the value of 2007Je07 is recommended here.

2.1 g Transitions

The γ-ray transition probabilities were calculated using the γ-ray emission intensities and the relevant internal conversion coefficients.

Multipolarities and mixing ratios of γ-ray transitions are from 1968Le07 and 1995Sh01. Multipolarities in square brackets are from level scheme (they are not measured).

The internal conversion coefficients (ICC) and their associated uncertainties for γ-ray transitions have been obtained using the BrIcc computer program, which uses the “Frozen Orbital” approximation (2002Ba85).

Experimental and theoretical conversion coefficients are compared in Table 2.

Table 2 - Comparison of theoretical and measured conversion coefficients

E_g/keV	Multipolarity	a(theory)	a(exp.)	
			1995Sh01	1999Gr33
53.81	M1	α_T=14.17, α_L=10.79 (16)	α_L=8 (4)	
96.3	M1+E2	α_T=5.6 , α_L=4.1 (18)	α_L>2.5	α_T=25 (15)
100.25	M1	α_T=11.97, α_L=1.758 (25)	α_L=1.2 (6)	
117.82	M1	α_T=7.58		α_T=13.5 (86)
150.21	M1	α_T=3.8, α_K=3.08 (5)	α_K=2.6 (5)	α_T=3.5 (9)
171.83	E2	α_T=0.863, α_K=0.226 (4)	α_K=0.3 (1)	α_T=0.84 (2)
218.12	E2	α_T=0.367, α_K=0.1375 (20)	α_K=0.14	
324.10	M1	α_T=0.446, α_K=0.362 (5)	α_K=0.4 (2)	
359.86	M1	α_T=0.335, α_K=0.272 (4)	α_K=0.4 (1)	
382.34	M1	α_T=0.284, α_K=0.231 (4)	α_K=0.25 (10)	
410.64	E2	α_T=0.0548, α_K=0.0344 (5)	α_K=0.03 (1)	

2.2 a Transitions

Measured energies of alpha particles are listed in table 3. Our recommended values are from 1968Le07 and 2002Gr36.

Table 3 - Measured and recommended values of α-particle energies (in keV) from ^{221}Fr α decay

1967Dz02	1968Le07[a]	2002Gr36	Recommended
		5500 (40)	5500 (40)
		5530 (25)	5530 (25)
	5689 (3)		5689 (3)
	5697 (4)		5697 (4)
	5776 (3)		5776 (3)
	5783 (4)		5783 (4)
	5813 (3)		5813 (3)
5930 (7)	5925 (3)		5925 (3)
5940 (6)	5938.9 (20)		5938.9 (20)
5966 (6)	5965.9 (25)		5965.9 (25)
5980 (6)	5979.9 (20)		5979.9 (20)
6075 (5)	6075.9 (20)		6075.9 (20)
6125 (5)	6126.3 (15)		6126.3 (15)
6241 (6)	6243.0 (20)		6243.0 (20)
6338 (5)	6341.0 (13)		6341.0 (13)

[a]: Values were adjusted based on the calibration recommendation of 1991Ry01.

Experimental and recommended α-particle emission probabilities are listed in Table 4. Our recommended alpha particle emission probabilities are average values of measured α-particle intensities with those deduced from γ-transition probability balance at each decay scheme level.

Table 4 - Experimental, recommended α-particle emission probabilities from ^{221}Fr decay

E_a(keV)	P_a(%)				
	1967Dz02	**1968Le07**	**2002Gr36**	**Deduced from Pg**	**Recommended†**
5500 (40)			3.3 (9) E-4	0.000038 (10)	0.000038 (10)
5530 (25)			9.0 (20) E-4	0.00010 (2)	0.00010 (2)
5689 (3)		0.002 (1)		0.0026 (5)	0.0025 (5)
5697 (4)		~0.001		~0.004	~0.003
5776 (3)		0.06 (1)		0.065 (4)	0.064 (4)
5783 (4)		0.005(2)		0.0029 (6)	0.0031 (6)
5813 (3)		0.004 (2)		0.006 (1)	0.006 (1)
5925 (3)	0.05 (1)	0.03 (1)		0.0280 (16)	0.0285 (24)
5938.9 (20)	0.13 (1)	0.17 (3)		0.127 (3)	0.128 (3)
5965.9 (25)	0.12 (1)	0.08 (1)		0.053 (4)	0.064 (16)
5979.9 (20)	0.46 (5)	0.49 (3)		0.27 (3)	0.39 (7)
6075.9 (20)	0.13 (2)	0.15 (3)		0.30 (6)	0.15 (3)
6126.3 (15)	14.5 (7)	15.1 (2)		15.3 (3)	15.1 (2)
6243.0 (20)	1.35 (7)	1.34 (10)		0.9 (5)	1.34 (7)
6341.0 (13)	83.2 (20)	83.4 (8)		82.9 (5)	82.8 (2)*

† Weighted average of values from the first four columns, normalized to a total of 100 %.

* Value reduced by a covariance effect introduced by the normalization to 100 %.

3. Atomic data

Atomic fluorescence yields (ω_K,ϖ_L, ϖ_M, η_{KL} and η_{LM}) are from Schönfeld (1996Sc06).

The X-ray and Auger electron emission probabilities have been deduced from γ-ray and conversion electron data by using the computer code RADLST. The deduced K X-ray emission probabilities P_{KX} = 2.77 (19) % agree with the measured value of 2.23 (20) % in 1995Sh01, thus confirming the completeness of the decay scheme.

4. Electron Emissions

The conversion electron emission probabilities have been deduced from γ-ray transition data using theoretical internal conversion coefficients.

5. Photon Emissions

5.1 g-ray energy values

The experimental and our recommended γ-ray energies from ^{221}Fr α decay are listed in table 5. Unless otherwise specified the later are averages (or weighted averages) from values given in 1968Le07, 1994Ar23, 1995Sh01, and 1999Gr33. γ-rays of 809.3 and 891.9 keV reported only in 2002Gr36 have also been included here. Several γ-rays observed in 1995Bu17 and 1994Ar23 were interpreted as sum peaks in 1999Gr33. Values from 1995Bu17 have not been included in this averaging because this reference seems to be an earlier publication of 1999Gr33 (notice that only these two references reported the 201.4- and 208.3-keV γ-rays).

Table 5 - Measured and recommended values of γ-ray energies for ^{221}Fr α decay.

1968Le07	1994Ar23	1995Bu17	1995Sh01	1999Gr33	2002Gr36	LWM	Recommended
		53.54 (18)	53.8 (1)	53.81 (3)		53.80 (28)	53.81 (3)
		68.11 (15)					
		96.12 (18	96.3 (3)	96.3 (3)		96.20 (14)	96.3 (3)
99.5	100.63 (2)	99.52 (6)	100.2 (1)	100.25 (2)		100.40 (24)	100.25 (2)
118.2 (2)	117.67 (5)	118.18 (9)	117.8 (2)	117.82 (3)		117.80 (9)	117.82 (3)
150.0 (2)	150.43 (5)	150.04 (4)	150.0 (1)	150.21 (3)		150.20 (8)	150.21 (3)
171.3	172.05 (5)	171.68 (4)	171.6 (1)	171.83 (3)		171.80 (8)	171.83 (3)
		201.44 (50)		201.4 (6)		201.4 (4)	201.4 (6)[a]
		208.3 (5)		208.3 (6)		208.3 (4)	208.3 (6)
217.99 (4)	218.30 (2)	218.14 (3)	218.0 (1)	218.12 (2)		218.20 (11)	218.12 (2)
	250.7 (2)						
	253.15 (15)						
		263.39 (14)					
	271.91 (5						
282.8	282.25 (5)	282.36 (15)	281.9 (3)	282.12 (9)		282.20 (4)	282.12 (9)
		297.11 (40)					
		299.59 (14)					
	310.20 (5)	310.14 (16)					
		314.11 (17)					
324.1	323.99	323.99 (6)	324.0 (2)	324.10 (6)		324.00 (4)	324.10 (6)
359.1	359.90 (2)	359.92 (6)	359.0 (2)	359.86 (4)		359.90 (6)	359.86 (4)
	368.17 (2)	368.18 (10)					
381.8	382.36 (2)	381.81 (4)	381.1 (2)	382.34 (4)		382.20 (15)	382.34 (4)
409.1	410.73 (2)	409.93 (7)	410.4 (2)	410.64 (5)		410.60 (16)	410.64 (5)
	435.68 (10)		437.8 (5)	437.00 (5)		436.4 (6)	437.00 (5)
		445.07 (20)	446.3 (8)	446.30 (8)		445.7 (6)	446.30 (8)
		469.6 (2)	469.0 (5)	468.3 (7)		469.40 (18)	468.3 (7)
			496.2 (10)				
	538.02 (10)	537.0 (2)	537.5 (8)	537.8 (8)		537.5 (5)	537.8 (8)
			562.3 (12)				562.3 (12)
		568.5 (3)	568.4 (10)	568.5 (3)		568.50 (21)	568.5 (3)
	577.76 (6)	576.9 (4)	577.0 (8)	576.9 (4)		577.70 (6)	576.9 (4)
				652 (2)			652 (2)
				658 (2)			658 (2)[a]
				665 (2)			665 (2)
					809.3 (2)		809.3 (2)
					891.9 (3)		891.9 (3)

[a]: not placed in level scheme.

5.2 Relative g-ray emission probabilities

Measured relative γ-ray intensities from ^{221}Fr are listed together with our recommended values in Table 6. Several γ-rays observed in 1995Bu17 and 1994Ar23 were interpreted as sum peaks in 1999Gr33. Thus their relative intensities may not be accurate so they have not been recommended here.

Results in 1995Sh01 are in agreement with those in 1999Gr33 within their experimental uncertainties, but they are not as complete and accurate. However, their decay scheme differs only by some weak transitions. For example, 1995Sh01 did not observe the 652-0, 578-368 γ-ray transitions, thus it did not propose the 652 keV level. 1999Gr33 is the most precise measurement among the available experimental data. Unless otherwise specified, the present recommended values are weighted averages (LWM) from values given in 1999Gr33, 1995Sh05, 1994Ar23. 1968Le07, and two γ-rays from 2002Gr36.

Table 6 - Measured and recommended relative γ-ray emission probabilities for ^{221}Fr

E_g(keV)	1968Le07	1994Ar23	1995Sh01	1999Gr33	2002Gr36	Recommended[&]
53.81 (3)			0.15 (4)	0.116 (27)		0.127 (22)
96.3 (3)			<0.09	0.063 (27)		0.058 (23)
100.25 (2)	0.95 (34)	1.47 (9)	1.33 (18)	0.89 (27)		1.37 (11)
117.82 (3)	0.34 (17)	0.328 (17)	0.044 (18)	0.20 (12)		0.19 (14)
150.21 (3)	0.69 (26)	0.362 (17)	0.53 (9)	0.420 (18)		0.393 (21)
171.83 (3)	0.52 (26)	0.517 (17)	0.58 (11)	0.680 (18)		0.60 (8)
201.4 (6)[a]				0.0098 (9)		0.0098 (9)†
208.3 (6)				0.045 (9)		0.045 (9)†
218.12 (2)	100	100	100	100		100
282.12 (9)	0.086	0.056 (9)	0.071 (27)	0.063 (9)		0.060 (6)
324.10 (6)	0.17 (9)	0.138 (9)	0.106 (27)	0.170 (9)		0.152 (10)
359.86 (4)	0.34 (17)	0.319 (17)	0.32 (9)	0.358 (18)		0.337 (12)
382.34 (4)	0.34 (17)	0.302 (17)	0.27 (9)	0.295 (18)		0.298 (12)
410.64 (5)	1.21 (34)	1.034 (86)	0.97 (18)	1.055 (18)		1.054 (17)
437.00 (5)		0.034 (6)	~0.009	0.0083 (9)		0.0083 (9)†
446.30 (8)			~0.009	0.0152 (36)		0.0152 (36)†
468.3 (7)			0.018 (9)	0.0152 (27)		0.0154 (26)
537.8 (8)		0.034 (10)	0.018 (9)	0.0447 (45)		0.039 (7)
562.3 (12)			~0.044			~0.044
568.5 (3)			~0.009	0.0107 (36)		0.0107 (36)†
576.9 (4)		0.041 (6)	0.035 (9)	0.0259 (36)		0.030 (5)
652 (2)				~0.00358		~0.00358†
658 (2)[a]				~0.00626		~0.00626†
665 (2)				~0.00805		~0.00805†
809.3 (2)					9.0E-4 (20)	9.0E-4 (20)*
891.9 (3)					3.3E-4 (9)	3.3E-4 (9)*

[&] Deduced using the LWM statistical method, unless otherwise specified.

[a] not placed in level scheme.

† From 1999Gr33

* Reported only in 2002Gr36

5.3 Absolute g-ray emission probabilities

Measurements of the absolute γ-ray emission probability of the 218.12 keV transition from ^{221}Fr α decay are listed in Table7.

Values in 1968Le07, 1986He06 and 1995Sh01 are the only absolute independent measurements. Among these absolute measurements, the one given in 1986He06 is the most precise.

1986He06 measured the γ-ray emission probability in equilibrium with ^{229}Th. ^{229}Th α-decay emits a 218.15-keV γ-ray, therefore this contribution should be subtracted.

1987He28 and 2000Ga52 measured γ-ray emission probabilities from the α-decay of ^{229}Th to ^{225}Ra relatively to I_γ = 4.3 for the 193.5-keV transition. They obtained 0.18 (2) and 0.134 (20) for the 218.15-keV γ-ray, respectively.

The weighted average of these values is 0.146 (20) relative to I_γ(193.5) = 4.3. Using a conversion factor of 1.026 (14) as given by 1987He28, the absolute value is: 0.146 (20) × 1.026 (14) = 0.150 (20) %.

Thus, the corrected absolute γ-ray emission probability of the 218.15-keV γ-ray from ^{221}Fr α decay is 11.57 (15) - 0.150 (20) = 11.42 (15) %, which is our recommended value.

Taking into account the β- branching ratio (see §6), the normalization factor between relative and absolute emission probabilities is N = 11.42 (15) / 0.999952 (15) = 0.1142 (15).

Table 7 - Measured and recommended absolute γ-ray emission probability of 218.12 keV for ^{221}Fr

P_g (218.12 keV)	References	Experimental value and method
12.5 (4)	1968Le07	
13.44 (27)	1981Di14	Ge(Li)
11.57 (15)	1986He06	Ge(Li),Au-Si surface barrier,in equilibrium with ^{229Th}
11.3 (10)	1995Sh01	Ge(Li),α-γ-ce coincidence
11.18 (15)	1999Gr33	Ge(Li),αγ coincidence, using I_α(6126)=15.1 (2) %
11.42 (15)	Recommended	Evaluated value, from 1986He06

[a]: value corrected using the evaluation of 1990Ak05.

The recommended absolute γ-ray emission probabilities are the recommended relative values shown in table 6 multiplied by 0.1142 (15), as given in table 8.

Table 8 - Absolute γ-ray emission probabilities from ^{221}Fr α decay.

E_g (keV)	P_g (%)		E_g (keV)	P_g (%)
53.8	0.0145 (25)		446.3	0.0017 (4)
96.3	0.007 (3)		468.3	0.0018 (3)
100.2	0.156 (13)		537.8	0.0045 (8)
117.8	0.022 (16)		562.3	0.005 (5)
150.2	0.0449 (25)		568.5	0.0012 (4)
171.8	0.069 (9)		576.9	0.0030 (6)
201.4	0.0011 (1)		652	0.0004 (4)
208.3	0.0051 (10)		658	0.0007 (7)
218.1	11.42 (15)		665	0.0009 (9)
282.12	0.0069 (7)		809.3	0.00010 (2)
324.1	0.0174 (12)		891.9	0.000038 (10)
359.9	0.0385 (15)			
382.3	0.0340 (14)			
410.6	0.1204 (25)			
437	0.0010 (1)			

6. b- Branching Ratio

Measured and recommended branching ratios for ^{221}Fr β^- decay are listed in Table 9. Our recommended β^- decay branching ratio from 1997Ch53 is I_{β^-} = 0.0048 (15) %. Thus, I_α = 99.9952 (15) %.

Table 9 - Measured and recommended branching ratio for ^{221}Fr β^- decay.

I_{b^-} (%)	References
0.0011 (5)	1995Ch74
0.0048 (15)	1997Ch53
0.0048 (15)	Recommended value, from 1997Ch53

7. References

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