^{59}Fe - Comments on evaluation of decay data

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This evaluation was originally completed by M.-M. Bé and V. Chisté in 2002 (2004BeZR) and was updated by V.P. Chechev in August 2014 to include new references on the ^{59}Fe half-life and decay energy and new internal conversion coefficients and thus to re-evaluate the half-life and to correct β^- - and γ - transition energies and probabilities.

1. DECAY SCHEME

The structure of the adopted decay scheme of ^{59}Fe is based on the evaluations of 2002Ba42 and 2004BeZR. ^{59}Fe disintegrates by 100 % beta minus emission to excited levels in ^{59}Co, mainly to the 1099 and 1291 keV excited levels.

The decay scheme is complete. Some authors (1974Mu12, 1974Ra13) carried out experiments in order to measure the weak β^-- branches. No clear evidence of a β^--branching to the ^{59}Co 1190 keV level was found; if this transition exists its branching ratio has an upper limit of 1×10^{-4}.

2. NUCLEAR DATA

Q^- value is from the 2012 mass evaluation by Wang *et al.* (2012Wa38).

The recommended half-life of ^{59}Fe is based on the experimental results given in Table 1.

Table 1. Experimental values of the ^{59}Fe half-life (in days)

N	Author(s) and year	Reference	$T_{1/2}$	Method and comments
1	Metzger (1952)	1952Me53	45.0 (30)	NaI(Tl)
2	Keene *et al.* (1958)	1958Ke26	44.56 (3)	Ionization chamber
3	Pierroux *et al.* (1959)	1959Pi43	45.60 (8)	Electrometer; *omitted* on the Chauvenet's criterion
4	Fuschini *et al.* (1960)	1960Fu03	63.1 (8)	*Omitted* on the Chauvenet's criterion
5	Heath *et al.* (1960)	1960He06	45 (5)	NaI(Tl)
6	Subba Rao (1960)	1960Su10	46.5 (10)	*Omitted* on the Chauvenet's criterion

7	Wortman and Langer (1963)	1963Wo01	45 (3)	
8	Emery *et al.* (1972)	1972Em01	44.5 (2)	NaI(Tl)
9	Visser *et al.* (1973)	1973Vi13	44.75 (4)	NaI(Tl)
10	Alstad *et al.* (1975)	1975Al02	45.3 (3)	Gas flow proportional counter
11	Houtermans *et al.* (1980)	1980Ho17	44.496 (7)	4πγ ionization chamber
12	Walz *et al.* (1983)	1983Wa26	44.53 (7)	4πγ pressurized ionization chamber
13	Unterweger *et al.* (1992)	1992Un01	44.5074 (72)	4πγ ionization chamber; *omitted* as superseded by 16
14	Martin *et al.* (1997)	1997Ma75	44.472 (8)	4π ionization chamber
15	Fitzgerald (2012)	2012Fi12	44.507 (7)	4πγ ionization chamber; *omitted* as superseded by 16
16	Unterweger and Fitzgerald (2014)	2014Un01	44.508 (16)	4πγ ionization chamber
Recommended value			**44.494 (12)**	

The values 3, 4, 6 have been rejected by the LWEIGHT computer program based on the Chauvenet's criterion. The values 13, 15 were not used because they were replaced ultimately by the later result 16 of the same laboratory.

The weighted average of the remaining 11 values is 44.494 d, the internal uncertainty is 0.005, the reduced-$\chi^2 / (\chi^2)_{crit}$ is 6.2/2.3, and the external uncertainty is 0.012. The largest contributions to the weighted average give the values 11 (49 %) and 14 (37 %), respectively. The unweighted average is 44.74 (9) d. The weighted average with the external uncertainty has been chosen as the recommended value. It conforms better to the most precise measurements than the unweighted average chosen by the LWEIGHT computer program (see also 2004BeZR).

Thus, the recommended value of ^{59}Fe half-life is **44.494 (12) days**.

Half-lives of ^{59}Co excited levels

Level 1100 keV

- Sidhu: ≤ 50 ps

- Béraud: < 14 ps

Level 1291 keV (in ns)

Author	NSR	Value	Uc
Sidhu	1967Si01	0.60	0.05
Agarwal	1967Ag03	0.59	0.02
Béraud	1967Be60	0.575	0.011
Garg	1972Ga39	0.538	0.004
Green	1972Gr05	0.564	0.020
Arens	1971Ar07	0.564	0.005

The value from Chauhan (0.516 (6)) was not taken into account: it seems that the experiment is the same as those described in Garg et al.

For the six values above the reduced χ^2 is 5.45 and the critical χ^2 = 3. Then, the uncertainty on the value given by Garg was increased by 1.08 in order to reduce its relative weight to 50 %. The reduced χ^2 is 5.10. This set of values is not consistent and the unweighted mean is adopted: 0.572 (34) ns.

Level 1434 keV

Arens: 210 (20) ps

2.1. Beta Transitions

The energies of β^- transitions have been obtained using the Q^- value and the ^{59}Co level energies (2002Ba42) deduced from the gamma-ray energies. The adopted from 2002Ba42 energies, J^π values and half-lives for the ^{59}Co excited levels are given in Table 2.

Table 2. ^{59}Co levels populated in the ^{59}Fe β^--decay

Level	Energy (keV)	Spin, parity	Half-life	$P_{\beta-}$ (%)
0	0	7/2−	Stable	0.18 (4)
1	1099.256 (3)	3/2−	3.1 (4) ps	53.30 (31)
2	1291.605 (5)	3/2−	551 (7) ps	45.19 (34)
3	1434.256 (5)	1/2−	210 (20) ps	1.25 (3)
4	1481.72 (12)	5/2−	166 (19) fs	0.080 (6)

The adopted β^- transition energies are compared with the available measurement values in Table 3.

Table 3. Measured and adopted β^- end-point energies (keV), in the ^{59}Fe decay

Reference	$\beta_{0,0}$	$\beta_{0,1}$	$\beta_{0,2}$	$\beta_{0,3}$	$\beta_{0,4}$
1952Me53	1560 (8)	462 (3)	271 (3)		
1960Be06		455 (5)	275 (5)		
1960Su10	1580 (20)	470 (6)	280 (6)	150 (10)	
1963Wo01	1573 (3)	475 (3)	273 (5)		
1974Mu12	1566			132	85
1974Ra13	1575 (20)	461 (10)	268 (10)	128	80
Adopted	**1565.0 (4)**	**465.7 (4)**	**273.4 (4)**	**130.7 (4)**	**83.3 (4)**

The probabilities of the β^--transitions $P_{\beta-}$ have been deduced from the P(γ+ce+ipc) balance at each level of ^{59}Co except for the $\beta_{0,0}$ transition for which $P_{\beta 0,0}$ = 0.18 (4) % has been adopted from the most precise measurement of 1974Ra13.

The β^- average energies and lg *ft* values have been calculated with the LOGFT code except the average energy and lg *ft* of the $\beta_{0,0}$ transition. For this second forbidden non unique transition, the β^- average energy of 584 keV has been adopted from the calculation with the SPEBETA computer program using the shape factor $p^2+1.7q^2$ from 1974Ra13. The latter was determined from fitting the calculated β^- spectrum to the measured one for the entire 0.47–1.57-MeV region unlike Wortman and Langer (1963Wo01) who restricted their fit to the 1.07-1.57-MeV region and obtained the different shape factor $p^2+3.3q^2$.

The lg *ft* value for $\beta_{0,0}$ transition has been taken from 1974Ra13.

The adopted probabilities and lg *ft* of β^--transitions are compared with the measured ones in Table 4.

Table 4. Measured and adopted probabilities and lg *ft* of β^--transitions in the ^{59}Fe decay

	1952Me53		1960Be06		1963Wo01		1974Ra13		Adopted	
	$P_\beta\times100$	lg *ft*	$P_\beta\times100$	lg *ft*	$P_\beta\times100$	lg *ft*	$P_\beta\times100$	lg *ft*		
$\beta_{0,0}$	0.3 (1)	10.9	< 0.5		0.30	10.96	0.18 (4)	11.15	**0.18 (4)**	**11.15**
$\beta_{0,1}$	54.8 (20)	6.7	55.4	6.1	51.2	6.74	51 (3)		**53.30 (31)**	**6.69**
$\beta_{0,1}$	44.9 (20)	5.9	44.6	5.3	48.5	5.92	47 (4)		**45.19 (34)**	**5.98**
$\beta_{0,3}+\beta_{0,4}$							1.4		**1.33 (3)**	

2.2. Gamma Transitions and Internal Conversion Coefficients

Gamma ray transition probabilities have been deduced from their gamma-ray emission probabilities, the total conversion coefficients ICC(s), and the internal pair creation coefficients IPC(s). The adopted ICC(s) are the theoretical values interpolated by the BRICC computer program (2008Ki07) from the tables of Band et al. (2002Ba85), accepting the "frozen orbital (no hole)" approximation, version v2.3S. The multipolarities and mixing ratio δ have been adopted from 2002Ba42 and 2004BeZR (for details see below). The IPC(s), α_π, have been calculated with the BRICC computer program.

Mixing multipolarity M1/E2 ratios, δ, for the 382 and 1482 keV gamma ray transitions have been taken from 2002Ba42.

The measured values of the mixing ratio, δ, for the 192 keV gamma ray transition are:

Author	**Mixing ratio, δ**
Pancholi	– 0.22 (2)
Eriksson	0.21 (2)
Arens	– 0.21 (2) or δ > 14
Bajaj	0.22 (2)
Collin	– 0.296 (23)
Adopted value	**0.211 (9)**

The mixing ratio, δ, of –0.008 (7) for the 143 keV gamma ray transition has been adopted from the survey of 1977Kr13. The measured values are:

Author	**Mixing ratio, δ**
Pancholi	– 0.15 (6) < δ < 0.026
Eriksson	– 0.006 (12)
Arens	0.028 + 0.009 – 0.014 or – 1.78 + 0.15 – 0.20
Adopted value **(from Krane 1977Kr13)**	**– 0.008 (7)**

The mixing ratio δ of −0.12 (6) for the 335 keV gamma ray transition has been adopted from 2004BeZR based on the measured values of:

Author	**Mixing ratio, δ**
Pancholi	– 0.12 (6)
Eriksson	– 0.12 (4)
Arens	+ 0.05 + 0.03 – 0.07 or – 1.8 + 0.4 – 0.6
Adopted value	**– 0.12 (6)**

A different δ value of +1.9 (3) has been adopted in the evaluation of Baglin (2002Ba52) from γ 335- γ 1099 angular correlations.

For pure E2 transitions, the adopted total ICC(s), α_T, are compared with the measured values in Table 5.

Table 5. Measured and adopted total ICC(s), α_T, for E2 transitions in the ^{59}Fe decay

Reference	**γ 1099 keV**	**γ 1291 keV**
1952Me53	$1.87\ (7) \times 10^{-4}$	$1.35\ (6) \times 10^{-4}$
1953Hi02	$1.84\ (27) \times 10^{-4}$	$1.06\ (16) \times 10^{-4}$
1964Co34	$1.36\ (10) \times 10^{-4}$	$1.07\ (8) \times 10^{-4}$
Adopted	$\mathbf{1.744\ (25) \times 10^{-4}}$	$\mathbf{1.217\ (16) \times 10^{-4}}$

Conversion electrons

Conversion electron intensities were calculated from the gamma transition probabilities and the internal conversion coefficients.

Hinman (1953Hi02) gives the ratio of the number of conversion electrons from the 1099 keV transition to the number of conversion electrons from the 1291 keV transition, to be equal to 1.91 (9).

There is a good agreement with the ratio (1.87) obtained from the calculated values in this evaluation.

3. ATOMIC DATA

The SAISINUC software has been used to determine the atomic data (fluorescence yields, X-ray energies and relative probabilities, and Auger electrons energies and relative probabilities).

4. PHOTON EMISSIONS

4.1. X-ray Emissions

The absolute emission probabilities of Co KX-rays have been calculated using the EMISSION computer program.

4.2. Gamma ray Emissions

The adopted energies of the 143, 192, 1099 and 1292 keV gamma rays are from 2000He14. The energies of the 335, 382 and 1482 keV gamma rays have been deduced from the adopted ^{59}Co level energies (Table 2). The measured energy values (1973Pa16) are: 334.8 (2) keV, 382.0 (4) keV and 1481.7 (2) keV.

Eight published papers (1959Fe15, 1960He06, 1964Co34, 1967Be17, 1970Le03, 1973Pa16, 1974Mu12, and 1989Mi07) describe measurements of the gamma emission intensities. Except for 1989Mi07, these measurements are relative to the intensity of the 1099 keV ray. Authors of the seven remaining papers converted their relative values (Table 6) to the absolute gamma emission intensities assuming 0.3 % for the $\beta_{0,0}$ transition probability.

Heath *et al.* (1960He06**)** did not give uncertainty, therefore these values are omitted.

The results given by Béraud *et al.* (1967Be17) are with uncertainties of the order of 10 %, they have not been omitted but their relative weight is generally weak, as well as those of the values given by Mukerji *et al.* (1974Mu12).

J. Legrand *et al.* (1970Le03) carried out coincidences measurements and deduced Pγ, absolute values, assuming that the β^- branching to the ground state is 0.3 %. The uncertainty adopted by Legrand is the sum of the statistical uncertainty assessed at 3σ and the systematic uncertainty at 1σ; consequently, the standard deviation cannot be obtained dividing the original uncertainty by 3 and we divided the given uncertainties by 2 only.

Pancholi *et al.* (1973Pa16) measured the relative values and normalized them such as P(γ+ce) (*1099* + *1292* + *1481*) = 99.7 %, assuming $P_{\beta-}$ (ground state) = 0.3 %.

Miyahara *et al.* (1989Mi07) carried out activity measurements and deduced absolute values. This paper is the most recent one and gives the most precise values which contribute more than 50 % in the adopted result for the two intense lines: 1099 and 1292 keV.

Table 6 summarizes all the values normalized to 100 for the 1099 keV line. These different sets of data are consistent, except for the original set of seven data for the 335 keV line where the corresponding values from 1959Fe15, 1964Co34 are outliers and have been omitted. The adopted values have been obtained with the LWEIGHT computer program.

Table 6. Experimental and adopted relative gamma ray intensities in the decay of ^{59}Fe

	Relative gamma ray intensities			
Reference	**γ 143 keV**	**γ 192 keV**	**γ 335 keV**	**γ 382 keV**
1959Fe18	1.52 (27)	4.3 (7)	0.61 (13)	
1964Co34	1.42 (36)	5.0 (5)	1.24 (5)	
1967Be60	1.4 (14)	4.4 (4)	0.44 (9)	0.039 (9)
1970Le03	1.76 (4)	5.31 (7)	0.43 (4)	0.041 (4)
1973Pa16	1.81 (7)	5.45 (18)	0.48 (2)	0.032 (5)
1974Mu12	1.91 (28)	5.7 (5)	0.47 (5)	
1989Mi07*	1.68 (5)	5.03 (9)	0.462 (28)	
Adopted value (LWM)	**1.73 (5)**	**5.15 (9)**	**0.46 (2)**	**0.038 (4)**

Table 6. Continued

	Relative gamma ray intensities		
Reference	**γ 1099 keV**	**γ 1292 keV**	**γ 1482 keV**
1959Fe18	100 (5)	79 (5)	
1964Co34	100.0 (27)	76.5 (27)	
1967Be60	100 (10)	77 (10)	0.100 (21)
1970Le03	100.0 (14)	79.5 (11)	0.162 (18)
1973Pa16	100.0 (27)	76.5 (19)	0.104 (11)
1974Mu12	100 (5)	73.7 (40)	0.090 (11)
1989Mi07*	100.0 (4)	75.8 (5)	
Adopted value (LWM)	**100.0 (4)**	**76.5 (5)**	**0.105 (11)**

*Absolute measurements in 1989Mi07: 143 keV – 0.955 (30) %, 192 keV – 2.851 (48) %, 335 keV – 0.262 (16) %, 1099 keV – 56.68 (22) %, 1292 keV – 42.99 (30) %.

The normalization factor (0.5651 (21) %) to convert the adopted relative gamma ray intensities to absolute emission probabilities has been deduced from the gamma ray transition intensity balance for the ground state assuming that the probability of the beta transition to the ^{59}Co ground state is 0.18 (4) % (1974Ra13).

5. ENERGY CONSERVATION

The total average energy of 1565 (5) keV, for one disintegration, calculated from the current evaluated data corresponds well to the available energy of 1565.0 (4) keV (Q^-) from the mass tables (2012Wa38) confirming the consistency of the decay scheme and the reliability of this evaluation.

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