^{24}Na - Comments on evaluation of decay data
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The first DDEP evaluation of ^{24}Na decay data was done by R.G. Helmer and E. Schönfeld in 2001 with a minor correction in 2004 (2004BeZR). The current evaluation has been completed in March 2014 with a literature cut-off by the same date.

1. DECAY SCHEME

The decay scheme of ^{24}Na is complete since the four levels populated in its β^- decay are the only excited levels in ^{24}Mg below the decay energy. The spins, parities, and half-lives of the excited levels are from the evaluation by Firestone (2007Fi14).

2. NUCLEAR DATA

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

The recommended half-life of ^{24}Na is based on the experimental results given in Table 1.

Table 1. Experimental values of the ^{24}Na half-life (in hours)

No.	Author(s) and year	Reference	$T_{1/2}$	Method and comments
1	Wilson and Bishop (1949)	1949Wi10	14.90 (2)	β counting
2	Cobble and Atteberry (1950)	1950Co69	15.10 (4)	Ionization chamber
3	Lockett and Thomas (1953)	1953Lo09	14.97 (2)	Electroscope
4	Tobailem (1955)	1955To07	14.90	Ionization chamber; *omitted* - no uncertainty
5	Campion and Merritt (1958)	1958Ca20	14.959 (10)	Proportional counter
6	Wolf(1960)	1960Wo07	14.953 (13)	Ionization chamber
7	Wyatt et al. (1961)	1961Wy01	15.05 (2)	Ionization chamber; *omitted* as superseded by 11
8	Monahan et al. (1962)	1962Mo21	15.04 (5)	Ionization chamber
9	Lagoutine et al. (1968)	1968La10	15.00 (2)	Ionization chamber; *omitted* as superseded by 19
10	Kemeny (1969)	1969Ke14	15.16 (5)	Ionization chamber; *omitted* - no background subtraction
11	Emery et al. (1972)	1972Em01	15.030 (3)	Ionization chamber; *omitted* as outlier
12	Chakraborty (1974)	1974Ch25	14.969 (12)	Ionization chamber; average of 6 values with external uncertainty

13	Genz et al. (1976)	1976Ge06	15.09 (6)	Ionization chamber
14	Davis et al. (1978)	1978Da21	15.010 (28)	Ionization chamber
15	Houtermans et al. (1980)	1980Ho17	14.9590 (12)	4πγ ionization chamber
16	Muckenheim et al. (1980)	1980Mu11	14.964 (15)	Ge(Li) detector
17	Rutledge et al. (1980)	1980RuZY	14.965 (10)	NaI(Tl) detector; *omitted* as superseded by 18
18	Rutledge et al. (1982)	1982RuZV	14.965 (10)	NaI(Tl) detector
19	Lagoutine, Legrand (1982)	1982La25	14.956 (3)	Ionization chamber
20	Hoppes et al. (1982)	1982HoZJ	14.951 (3)	4πγ ionization chamber; *omitted* as superseded by 24
21	Walz et al. (1983)	1983Wa26	14.9575 (28)	4πγ ionization chamber
22	Abzouzi et al. (1989)	1989Ab05	15.027 (2)	γ counting, NaI(Tl), Ge-detectors; *omitted* as outlier
23	Bode et al. (1991)	1991Bo34	14.90 (2)	γ counting, a well-type NaI(Tl), Ge- detectors
24	Unterweger *et al.* (1992)	1992Un01	14.9512 (32)	4πγ ionization chamber; *omitted* as superseded by 26
25	Mignonsin (1994)	1994Mi03	14.86 (12)	γ counting, GeLi detector
26	Unterweger *et al.* (2002)	2002Un02	14.951(3)	4πγ ionization chamber; *omitted* as superseded by 27
27	Unterweger and Lindstrom (2004)	2004Un01	14.9512 (32)	4πγ ionization chamber; *omitted* as superseded by 29
28	Lindstrom *et al.* (2005)	2005Li66	14.959 (9)	γ counting, Ge detector, 4πγ ionization chamber
29	Fitzgerald (2012)	2012Fi12	14.951 (3)	4πγ ionization chamber; *omitted* as superseded by 30
30	Unterweger and Fitzgerald (2014)	2014Un01	14.955 (7)	4πγ ionization chamber
Recommended value			**14.958 (2)**	**LWM**

Value 4 has been omitted as it is reported without uncertainty. Value 10 has been omitted as it was obtained without background subtraction. The values 7, 9, 17, 20, 24, 26, 27, 29 were not used because they were replaced ultimately by later results of the same laboratory.

In the final weighted average, the values of 11 (1972Em01) and 22 (1989Ab05) have been omitted because they are outliers; both are over 30 σ from the adopted value. If these values are included, the reduced χ^2 / $(\chi^2)_{crit}$ value is about 70/2. For the 18 values included, the LWEIGHT computer program using the limitation of relative statistical weight method (LWM) has increased the uncertainty of the value 15 (1980Ho17) from 0.0012 to 0.0018 in order to reduce its relative weight from 69% to 50%. In addition to this relative weight, those of the values of 1982La25 and1983Wa34 are 17% and 20%.

For the final weighted average of 14.958 the internal uncertainty is 0.0013, the reduced-χ^2 / $(\chi^2)_{crit}$ value is 2.6/2.0, and the external uncertainty is 0.0020. The LWEIGHT program has chosen the weighted average with the external uncertainty.

The recommended value of ^{24}Na half-life is **14.958 (2) hours**. It can be compared with earlier evaluations of 14.9574 (20) h (2004BeZR) and 14.997 (12) h (2007Fi14).

2.1. Beta Transitions

The energies of β^- transitions have been obtained using the Q^- value and the ^{24}Mg level energies adopted from 2007Fi14 (Table 2). The probabilities of β^--transitions $P_{\beta-}$ have been deduced from the P(γ+ce) balance at each level of ^{24}Mg.

Table 2. ^{24}Mg levels populated in ^{24}Na β^--decay

Level	Energy (keV)	Multipolarity	Half-life	β^--transition probability (%)
0	0	0+	Stable	$< 5 \times 10^{-10}$
1	1368.672 (5)	2+	1.33 (6) ps	0.003 (2)
2	4122.889 (12)	4+	22 (2) fs	99.930 (3)
3	4238.24 (3)	2+	41 (4) fs	< 0.002
4	5235.12 (4)	3+	61 (7) fs	0.066 (3)

Below the nine experimentally determined values of the β^--end-point energy (in keV) for the transition to the 4123-keV level are compared with the value derived from the Q value.

Energy, keV	**Reference**	**Author(s) and year**
1394 (4)	1957Po36	Porter et al. (1957)
1389 (4)	1958Da10	Daniel (1958)
1389 (2)	1961De25	Depommier and Chabre (1961)
1395	1963Pa20	Paul et al. (1963)
1393 (3)	1964Le09	Lehmann (1964)
1394 (2)	1965Be24	Beekhuis and De Waard (1965)
1389.2 (5)	1969Bo48	Booij et al. (1969)

1389 (2)	1972Gi17	Gils et al. (1972)
1390 (1)	1976Ge06	Genz et al. (1976)
1392.72 (4)	**Q - E_{level} (4123 keV)**	

The measured and adopted (calculated) probabilities (in %) of the β - transitions are:

Level Energy (keV)	1950Gr01 Grant (1950)	1951Tu12 Turner (1951)	**Adopted β – transition probabilities**
5235			**0.066 (3)**
4238			**0.001 (1)**
4123	100	100	**99.930 (3)**
1369	< 0.01	0.003	**0.003 (2)**
0			**0**

The 4th forbidden β^--branch to the ground state has not been observed. As discussed by Helmer and Schönfeld in 2004BeZR, from the experimental limit on the number of counts in the β^--spectrum above 4140 keV, the authors of 1951Tu12 give lg ft > 15.1. The lg ft systematics of 1998Si17 lists four decays of this type with lg ft values of 22.5 to 24.3. Since this is a very small set of values, for ^{24}Na the lower limit of the lg ft can be taken to be 20, which corresponds to the transition probability to the ground state $P_{\beta-}$ (0) < 5 ×10^{-10} %; hence no direct transition to the ground state has been adopted.

The β^--branch to the 4238 keV level is a 2nd forbidden transition and the lg ft systematics (1998Si17) give lg ft > 10.6 which corresponds to the transition probability to the 4238 keV level $P_{\beta-}$ (4238) < 0.002 %; a value of 0.001 (1) % has been adopted. The negligible probability of this transition is supported by the adopted decay scheme for which the intensity of the 997-keV γ-ray feeding this level is more [0.00145 (25)] than that depopulating it [0.0011 (1) = 0.00025 (3) + 0.00084 (10)]. An unobserved γ-ray of 116 keV also theoretically depopulating this level could improve the intensity balance.

Therefore, no direct β^--transition to the ground state and a transition probability of 0.001 (1) % to the level of 4238 keV, are present in the adopted ^{24}Na decay scheme.

No direct measurements are reported for the β^--transitions to the 4238- and 5235-keV levels. The adopted value for the transition to the 1369-keV level is compatible with the measurement of 1951Tu12 who gave no uncertainty. The adopted value for the transition to the

5235-keV level was calculated from probabilities of the two de-exciting γ-rays and their electron and pair conversion.

2.2. Gamma Transitions and Internal Conversion Coefficients

The adopted ICC(s) and α_π 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. The multipolarities and mixing ratios δ have been taken from 2007Fi14.

The transition probabilities of the 3866- and 4238-keV γ-rays have been determined from the following measurements of the γ-ray emission probabilities:

Reference	Author(s) and year	Pγ(3866 keV) (%)	Pγ(4238 keV) (%)
1960Ar10	Artamonova et al. (1960)	0.09 (2)	0.0015 (5)
1962Mo21	Monahan et al. (1962)	0.075 (20)	0.008 (3)
1968Va06	van Klinken et al. (1968)	0.063 (6)	
1970Le12	Lebowitz (1970)	0.0489 (25)	< 0.0033
1972Ra21	Raman et al. (1972)	0.061 (5)	0.00084 (10)
2003Ep02	Epp and Griffin (2003)	0.067 (2)	0.00085 (39)
Adopted value		**0.066 (2)**	**0.00084 (10)**

For the 3866-keV γ-ray, the value of 1970Le12 has been omitted because this value is too low (outlier). If this value is included, the reduced χ^2 / $(\chi^2)_{crit}$ value is about 7/3. For the 5 values included, a weighted average is 0.0662 with an internal uncertainty of 0.0018 and external uncertainty of 0.0016, the reduced- χ^2 / $(\chi^2)_{crit}$ value is 0.8/3.3. The LWEIGHT code has chosen the weighted average and internal uncertainty. The smallest experimental uncertainty is 0.002. Thus, the adopted value of Pγ (3866 keV) is 0.066 (2) %.

For the 4238-keV γ-ray, the adopted value is the average of three values (1962Mo21, 1972Ra21, 2003Ep02) which is consistent with the limit of 1970Le12.

The 997- and 2869-keV γ-ray transitions are not observed in ^{24}Na decay, but their emission probabilities can be deduced from the relative probabilities in other decays or reactions. The transition probability of 997-keV γ-ray was calculated from the measured Pγ(997)/Pγ(3866) ratio. For this ratio, the measured values are:

Pγ(997)/Pγ(3866)	Reference	Author(s) and year
0.017 (5)	1972Me09	Meyer et al. (1972) from ^{23}Na(p,γ)

0.019 (2)	1973Le15	Leccia et al. (1973) from ^{23}Na(p,γ)
0.015 (3)	1975Bo43	Boydell et al. (1975) from ^{23} Na(p,γ)
0.0260 (17)	1981Wa07	Warburton et al. (1981) from ^{24}Al ε - decay
0.030 (4)	1990En02	Endt et al. (1990) from ^{23}Na(p,γ)
0.022 (4)	**Adopted value**	

The adopted value is the weighted average value of 0.022, a reduced- $\chi^2 / (\chi^2)_{crit}$ value is 4.6/3.3. The LRSW method increases the final uncertainty to 0.004 to include the most precise value of 0.0260. With the above value of Pγ(3866), we obtain Pγ(997) = 0.00145 (25).

The ratio **Pγ(2869)/Pγ(4238**) has been measured as follows:

Pγ(2869)/Pγ(4238)	**Reference**	**Author(s) and year**
0.30 (3)	1972Me09	Meyer et al. (1972) from ^{23}Na(p,γ)
0.30 (3)	1972Ra21	Raman et al. (1972) from ^{23}Mg(n,n'γ)
0.299 (15)	1973Le15	Leccia et al. (1973) from ^{23}Na(p,γ)
0.267 (7)	1973Br16	Branford (1973) from ^{23}Na(p,γ)
0.299 (19)	1975Bo43	Boydell (1975) from ^{23}Na(p,γ)
0.304 (19)	1981Wa07	Warburton et al. (1981) from ^{24}Al ε decay
0.300 (15)	**Adopted value**	

The value of 1973Br16 has been omitted as an outlier. For the final weighted average of 0.3003 the internal uncertainty is 0.0090, the reduced- $\chi^2 / (\chi^2)_{crit}$ value is 0.01/3.3, and the external uncertainty is 0.0010. The LWEIGHT program has chosen the weighted average with the internal uncertainty. The smallest experimental uncertainty is 0.015. The adopted value is 0.300 (15).

With the above adopted value of 0.00084 (10) for Pγ(4238), one obtains Pγ(2869) = 0.00025 (3).

If there are no direct feeding the ground state by β^--decay or the unobserved γ transitions of 4123 and 5235 keV, Tγ(1369) = 100 – Tγ(4237) = 99.99916 (10) where Tγ =Pγ (1.0 + α_T + α_π). Upper limits for transition intensities of the 4123- and 5235-keV γ-rays can be determined from the ratios measured by 1981Wa07: Pγ(4123)/Pγ(2754) < 0.00001, or Pγ(4122) < 0.001 and Pγ(5235)/Pγ(3866) < 0.004, so Pγ(5235) < 0.00023 and by 1972Ra21 and 1967En05 which give Pγ(4123) < 0.0009 and Pγ(5235) < 0.00002. If the 4123- and 5235-keV transitions have intensities equal to the latter upper limits, the value of Tγ(1369) would reduce from 99.99916 to 99.9983. Since it is unlikely that these two values will be at the limits, we have adopted the value of **Tγ(1369) = 99.9990 (3)** (see also 2004BeZR) and from here **Pγ(1369) = 99.9934 (5) %.**

The 1112-keV transition between the 5235- and 4123-keV levels has not been observed in ^{24}Na decay. In the ^{24}Al decay, the authors of 1981Wa07 have found an upper limit of the ratio Pγ(1112)/Pγ(3866) < 0.007 which yields the value of Pγ(1112) < 0.0004.

The transition probability of the 2754-keV γ-ray has been calculated from the balance condition Tγ(2754) = Tγ(1369) - [Tγ(2869) + Tγ(3866) + Pβ^-(4147)]. This yields **Tγ(2754) =** 99.9990 (3) - 0.069 (3) = **99.930 (3) %**, which gives **Pγ(2754) = 99.862 (3) %.**

From the intensity balance at the 4238-keV level, for a possible depopulating γ-ray of 116 keV, Pγ(116) = 0.0004 (3) + Iγ(4238). Since this γ-ray has not been observed, it is omitted from the scheme.

The internal-pair formation coefficients (α_π) for the 1369- and 2754-keV γ-rays calculated by the BrIcc code (2008Ki07) can be compared with measured values:

α_π (1369 keV)	α_π (2754 keV)	Reference
0.00116 (10)		1949Ra01
0.00076 (19)		1950Mi82
0.00067 (10)		1951Cl50
0.00006 (1)	0.00071 (2)	1952Bl53
0.00003	0.00080	1952Sl52
0.0000463 (7)	**0.000675 (10)**	**adopted (calculated)**

3. ATOMIC DATA

The atomic data (fluorescence yields, X-ray energies and relative probabilities, and Auger electrons energies and relative probabilities) have been deduced by using the SAISINUC software.

4. ELECTRON EMISSIONS

The energies of the conversion electrons and the energies of the electrons from the internal-pair creation process have been obtained from the gamma-ray transition energies. The absolute emission probabilities of the conversion electrons have been deduced using recommended Pγ, ICC and α_π values.

The absolute emission probabilities of K and L Auger electrons have been calculated using the EMISSION computer program.

β^- average energies have been calculated using the LOGFT computer program.

5. PHOTON EMISSIONS

5.1. X-ray Emissions

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

5.2. Gamma ray emissions

The energies of gamma rays in ^{24}Mg have been obtained from the adopted level energies using the SAISINUC code.

The number of photons per disintegration was deduced as described in sect. 2.2.

6. ENERGY CONSERVATION

The total average energy of 5515.63 (12) keV, for one disintegration, calculated from the current evaluated data corresponds very well to the available energy of 5515.61 (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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