

## Comments of <sup>24</sup>Na Evaluation by R. G. Helmer and E. Schönfeld

### 1 Decay Scheme

The decay scheme is complete since the four levels populated in this decay are the only excited levels in <sup>24</sup>Mg below the decay energy.

The spins, parities, and half-lives of the excited levels are from the Endt evaluation 1990En08.

### 2 Nuclear Data

For the half-life, the following values are available (in hours):

14.90 (2)	1949Wi10, Wilson and Bishop (1949)	
15.10 (4)	1950Co69, Cobble and Atteberry (1950)	
14.97 (2)	1953Lo09, Lockett and Thomas (1953)	
14.90	1955To07, Tobailem (1955)	omitted - no uncertainty
14.959 (10)	1958Ca20, Campion and Merritt (1958)	
14.953 (13)	1960Wo07, Wolf(1960)	
15.05 (2)	1961Wy01, Wyatt et al. (1961)	superseded by 1972Em01
15.04 (5)	1962Mo21, Monahan et al. (1962)	
15.00 (2)	1968La10, Lagoutine et al. (1968)	superseded by 1982La25
15.16 (5)	1969Ke14, Kemeny (1969)	omitted - no background subtraction
15.030 (3)	1972Em01, Emery et al. (1972)	omitted - outlier
14.969 (12)	1974Ch25, Chakraborty (1974); average of 6 values with external uncertainty	
15.09 (6)	1976Ge06, Genz et al. (1976)	
15.010 (28)	1978Da21, Davis et al. (1978)	
14.9590 (12)	1980Ho17, Houtermans et al. (1980)	
14.964 (15)	1980Mu11, Muckenheim et al. (1980)	
14.965 (10)	1980RuZY, Rutledge et al. (1980)	superseded by 1982RuZY
14.965 (10)	1982RuZV, Rutledge et al. (1982)	
14.956 (3)	1982La25, Lagoutine, Legrand (1982);	originally $\sigma=0.008$ divided by 3
14.951 (3)	1982HoZJ, Hoppes et al. (1982)	superseded by 1992Un01
14.9575 (28)	1983Wa26, Walz et al. (1983)	
15.027 (2)	1989Ab05, Abzouzi et al. (1989)	omitted - outlier
14.90 (2)	1991Bo34, Bode et al. (1991)	
14.9512 (32)	1992Un01, Unterweger et al. (1992)	
14.86 (12)	1994Mi03, Mignonsin (1994)	

**14.9574 (20) adopted value**, LRSW weighted average

In the final weighted average, the values of 1972Em01 and 1989Ab05 have been omitted because they are outliers; both are over  $30\sigma$  from the adopted value. If these values are included, the reduced- $\chi^2$  value is about 80. For the 17 values included, the Limitation of Relative Statistical Weight, LRSW, method (1985ZiZY, 1992Ra08) increases the uncertainty of the value of 1980Ho17 from 0.001

to 0.0016 in order to reduce its relative weight from 73% to 50%. In addition to this relative weight, those of the values of 1982La25, 1983Wa34, and 1992Un01 are between 13 and 15%. For the final weighted average the internal uncertainty is 0.0012, the reduced- $\chi^2$  value is 3.01, and the external uncertainty is 0.0020.

1974Ch25 have measured this half-life for solid NaCl and for an aqueous solution. No change of the half-life was observed, contrary to the report of 1969Ke14.

The  $Q_{\beta^-}$  value is taken from the 1995Au04 evaluation.

## 2.1 $\beta^-$ Transitions

The energies are calculated from the  $Q_{\beta^-}$  value and the level energies. In the following list, nine values of the experimentally determined  $\beta^-$  end-point energy (in keV) for the transition to the 4122-keV level are compared with the value derived from  $Q$  value.

1394 (4)	1957Po36, Porter et al. (1957)
1389 (4)	1958Da10, Daniel (1958)
1389 (2)	1961De23, 1965De25, 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)
1392.94 (16)	$Q - E(4122)$

The measured and calculated probabilities (in %) of the  $\beta^-$  transitions are:

Level (keV)	1950Gr01 Grant(1950)	1951Tu12 Turner (1951)	Present evaluation
5236			0.057 (7)
4239			<0.002
4122	100	100	99.939 (8)
1368	<0.01	0.003	0.003 (2)
0			$<5 \times 10^{-10}$

The 4<sup>th</sup> forbidden  $\beta^-$  branch to the ground state has not been observed. From the experimental limit on the number of counts in the  $\beta^-$  spectrum above 4140 keV, 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, we have taken the lower limit of the <sup>24</sup>Na  $\lg ft$  to be 20, which corresponds to  $I_{\beta^-}(0) < 5 \times 10^{-10}$  %; this value is adopted.

The  $\beta^-$  branch to the 4238 level is a 2<sup>nd</sup> forbidden transitions and the  $\lg ft$  systematics (1998Si17) give  $\lg ft > 10.6$  which corresponds to  $I_{\beta^-}(4238) < 0.002$  %; this value is adopted. This small value is supported by the adopted decay scheme for which the intensity of the 998-keV  $\gamma$ -ray feeding this level is more [0.00151(25)] than that depopulating it [0.00024(3) + 0.00084(10)]. An unobserved  $\gamma$ -ray of 116 keV could also depopulate this level.

No direct measurements are reported for the  $\beta^-$  transitions to the 4238- and 5236-keV levels. The adopted value for the transition to the 1368-keV level is based on the measurement of 1951Tu12 [Turner and Cavanagh (1951)] who gave no uncertainty. The adopted value for the transition to the 5236-keV level was calculated from probabilities of the two de-exciting  $\gamma$ -rays and their internal and pair conversion.

The  $\beta^-$  branch to the 4122-keV level is 100% less the intensity of those to the levels at 0, 1368, 4238, and 5236 keV. The sum of the latter four is 0.061(8)%, so the former is 99.939(8)%.

## 2.2 Gamma Transitions

The transition probabilities of the 3866- and 4237-keV  $\gamma$ -rays are determined from the following measurements:

	3867 keV	4237 keV
1960Ar10, Artamonova <i>et al.</i> (1960)	0.09 (2)	0.0015 (5)
1962Mo21, Monahan <i>et al.</i> (1962)	0.075 (20)	0.008 (3)
1968Va06, van Klinken <i>et al.</i> (1968)	0.063 (6)	
1970Le12, Lebowitz (1970)	0.0489 (25)	<0.0033
1972Ra21, Raman <i>et al.</i> (1972)	0.061 (5)	0.00084 (10)
<b>Adopted value</b>	<b>0.056(7)</b>	<b>0.00084(10)</b>

For the 3866-keV  $\gamma$ -ray, the adopted value is the average of all five values, which gives an internal uncertainty of 0.0026, a reduced- $\chi^2$  value of 2.46, and an external uncertainty of 0.0041, and the final uncertainty was expanded to include the most precise value. For the 4237-keV  $\gamma$ -ray, the value of 1972Ra21 is adopted as it is considered to be the most reliable and it is consistent with the limit of 1970Le12.

The 996- and 2869-keV  $\gamma$ -ray transitions are not observed in <sup>24</sup>Na decay, but their emission probabilities can be deduced from the relative probabilities in other decays or reactions. The transition probability of 996-keV  $\gamma$ -ray was calculated from the measured  $P_\gamma(996)/P_\gamma(3866)$  ratio. For this ratio, the measured values are :

0.017 (5)	1972Me09, Meyer <i>et al.</i> (1972) from <sup>23</sup> Na(p, $\gamma$ )
0.019 (2)	1973Le15, Leccia <i>et al.</i> (1973) from <sup>23</sup> Na(p, $\gamma$ )
0.015 (3)	1975Bo43, Boydell <i>et al.</i> (1975) from <sup>23</sup> Na(p, $\gamma$ )
0.0260 (17)	1981Wa07, Warburton <i>et al.</i> (1981) from <sup>24</sup> Al $\epsilon$ decay
0.030 (4)	1990En02, Endt <i>et al.</i> (1990) from <sup>23</sup> Na(p, $\gamma$ )
<b>0.022 (4)</b>	<b>Adopted value</b>

The adopted value is the weighted average value of 0.0222 with an internal uncertainty of 0.0011, a reduced- $\chi^2$  of 4.6 and an external uncertainty of 0.0024. The LRSW method increases the final uncertainty to 0.004 to include the most precise value of 0.0260. With the above value of  $P_\gamma(3866)$ , we obtain  $P_\gamma(996) = 0.00123(27)$ .

The ratio  $P_\gamma(2869)/P_\gamma(4237)$  ratio has been measured as follows:

0.30 (3)	1972Me09, Meyer <i>et al.</i> (1972) from <sup>23</sup> Na(p, $\gamma$ )
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0.30 (3)	1972Ra21, Raman <i>et al.</i> (1972) from <sup>24</sup> Mg(n,n'γ)
0.299 (15)	1973Le15, Leccia <i>et al.</i> (1973) from <sup>23</sup> Na(p,γ)
0.267 (7)	1973Br16, Branford (1973) from <sup>23</sup> Na(p,γ)
0.299 (19)	1975Bo43, Boydell (1975) from <sup>23</sup> Na(p,γ)
0.304 (19)	1981Wa07, Warburton <i>et al.</i> (1981) from <sup>24</sup> Al ε decay

**0.284 (7) Adopted value**

The adopted value is the weighted average of all six values after the uncertainty for the 1973Br16 value was increased from 0.007 to 0.009 to reduce its relative weight from 63% to 50%. This average has an internal uncertainty of 0.006, a reduced-χ<sup>2</sup> of 1.37, and an external uncertainty of 0.007. With the above adopted value of 0.00084(10) for P<sub>γ</sub>(4237), one obtains P<sub>γ</sub>(2869) = 0.00024(3).

If there are no direct feeding the ground state by β<sup>-</sup> decay or the unobserved γ transitions of 4122 and 5236 keV, T<sub>γ</sub>(1368) = 100 - T<sub>γ</sub>(4237) = 99.99916(10) where T<sub>γ</sub> = P<sub>γ</sub> (1.0 + α + α<sub>π</sub>). Upper limits for transition intensities of the 4122- and 5236-keV γ-rays can be determined from the ratios measured by 1981Wa07: P<sub>γ</sub>(4122)/P<sub>γ</sub>(2754) < 0.00001, or P<sub>γ</sub>(4122) < 0.001 and P<sub>γ</sub>(5236)/P<sub>γ</sub>(3867) < 0.004, so P<sub>γ</sub>(5236) < 0.00023 and by 1972Ra21 and 1967En05 which give P<sub>γ</sub>(4122) < 0.0009 and P<sub>γ</sub>(5236) < 0.00002. If the 4122- and 5236-keV transitions have intensities equal to the latter upper limits, the value of T<sub>γ</sub>(1368) 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 T<sub>γ</sub>(1368) = 99.9990(3) and P<sub>γ</sub>(1368) = 99.9935(5).

The 1114-keV transition between the 5236- and 4122-keV levels has not been observed in <sup>24</sup>Na decay. In the <sup>24</sup>Al decay, 1981Wa07 have found an upper limit of the ratio P<sub>γ</sub>(1114)/P<sub>γ</sub>(3867) < 0.007 which yields the value of P<sub>γ</sub>(1114) < 0.0004.

The transition probability of the 2754-keV γ-ray is calculated from the balance condition T<sub>γ</sub>(2754) = T<sub>γ</sub>(1368) - [T<sub>γ</sub>(2869) + T<sub>γ</sub>(3867) + P<sub>β<sup>-</sup></sub>(1368)]. This yields T<sub>γ</sub>(2754) = 99.9990(3) - 0.059(7) = 99.940(7)%, which gives P<sub>γ</sub>(2754) = 99.872(8)%.

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

The internal-conversion coefficients are interpolated from the tables of theoretical values (Band *et al.*, 1976). The mixing parameters, δ, were based on the following information:

γ energy	1960Ba19	1963Br15	1973Le15	<b>adopted</b>
998			-5.1 (+8-12) or -0.47 (4)	<b>-0.47 (4)</b>
2869	+23 (9)		> 30	<b>+23 (9)</b>
3867		large	-0.21 (2) or >19	<b>pure E2</b>

The uncertainty of the interpolated conversion coefficients is assumed to be 3 %.

The internal-pair-formation coefficients (α<sub>π</sub>) for the 1368- and 2754-keV γ-rays have been interpolated from calculated values of 1979Sc31 and are in reasonable agreement with measured values which are:

1368 keV	2754 keV
	0.00116 (10) 1949Ra01
	0.00076 (19) 1950Mi82

	0.00067 (10)	1951Cl50
0.00006 (1)	0.00071 (2)	1952Bl53
0.00003	0.00080	1952Sl52

In summary, the  $\gamma$ -ray photon and transition intensities are:

Energy (keV)	Transition (%)	Photon (%)
998	0.00151 (25)	
1114	<0.0004	
1368	99.9990 (3)	99.9935 (5)
2869	0.00024 (3)	
2754	99.940 (7)	99.872 (8)
3867	0.056 (7)	
4122	<0.0009	
4238	0.00084 (10)	
5236	<0.00002	

If  $P_\gamma$  is not given, it is equal to  $T_\gamma$ .

### 3 Atomic Data

The values for  $\omega_K$ , the mean  $\omega_L$ , and  $\eta_{KL}$  are taken from 1996Sc06.

#### 3.1 X Radiation

The mean energies of the  $K_\alpha$  radiations have been calculated from the wave lengths given by 1967Be65.

#### 3.2 Auger Electrons

The mean energy of the KLL Auger electrons is taken from 1977La19.

## 4 Radiation Emission

### 4.1 Electron Emission

The energies and emission probabilities of the particles are the same as those given already in sect. 2.1. The energies of the electron from internal conversion and internal-pair formation are calculated from the  $\gamma$ -ray energies. The number of electrons per disintegration for various processes are calculated from the  $\gamma$ -ray emission probabilities,  $\alpha_{\tau}$ ,  $\alpha$ , and the atomic data.

### 4.2 Photon Emission

The energies of the two main  $\gamma$ -rays are from 2000He14. From the decay of <sup>24</sup>Na, the energies for the 3867- and 4238-keV  $\gamma$ -rays are 3867.5(3) from 1968Va06 and 1970Le12 and the 4237.4(10) keV from 1972Ra21. The energies of the 996- and 2869-keV  $\gamma$ -rays would then be calculated from the level energies. The adopted values for all four of these  $\gamma$ -rays have been taken from the decay of <sup>24</sup>Al (1981Wa07).

The number of photons per disintegration were calculated as described in sect. 2.2.

## 5 Main Production Modes

Taken from N. Coursol, Table de Radionucléides (1982).

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