^{211}Bi – Comments on Evaluation of Decay Data
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This evaluation was completed in July 2009. The literature available by December 31st, 2008 was included.

1. Evaluation Procedures

The Limitation of Relative Statistical Weight (LWM) method was applied for averaging numbers throughout this evaluation; this method was implemented by using the computer code LWEIGHT, ver. 4 (designed for Excel, MS Office). The uncertainty assigned to an average value in this evaluation is never lower than the lowest uncertainty of any of the experimental input values.

2. Decay Scheme

^{211}Bi decays 99.724 (4) % by alpha particle emissions, populating the ^{207}Tl ground state (83.56 (23) %) and the 351.03 keV excited state (16.16 (23) %). ^{211}Bi has also a weak beta minus decay branch (0.276 (4) %) to the ground state of ^{211}Po; although these β^- particles were not observed experimentally (the low intensity beta-particle emission is obscured by the intense β^- particles emission from the ^{211}Pb sources used for measurements), the existence of the beta minus decay and the adopted value of the corresponding branching ratio are based on the alpha-particle spectrometry measurements of the emission probabilities ratio, $I\alpha(^{211}Po)/(I\alpha(^{211}Po)+I\alpha(^{211}Bi))$, performed by several scientists (see references from Table 1). The adopted value represents the weighted mean of the experimental results published in the literature (see also Table 1, below); an earlier value, 0.32 % (without a quoted uncertainty), determined by Rutherford et al. (1931), was not taken into account. Another important study of the ^{211}Bi decay scheme is presented in the reference 1966Go13. The most recent evaluations of the ^{211}Bi nuclear structure, alpha and beta minus decay data, published in Nuclear Data Sheets, were made by M. J. Martin (1993) and E. Browne (2004). In the present evaluation, the spin and parity of the levels have been adopted from the above mentioned A = 207 and A = 211 ENSDF mass-chain evaluations (1993Ma73 and 2004Br45, respectively).

Table 1: Beta minus branching ratio for the ^{211}Bi decay

Beta minus branching ratio (experimental), %	Reference
0.274 (4)	1967Da10
0.274 (10)	1965Nu03
0.29 (1)	1962Gi04
Recommended value: 0.276 (4) %	

3. Nuclear Data

The adopted alpha decay energy value $Q(\alpha)$ = 6750.33 (46) keV, is from 2003Au03. This value is in very good agreement with the effective $Q(\alpha)$ value of 6750.63 keV (with an uncertainty of 0.21 keV), calculated from the decay scheme data, by using the SAISINUC software, version 2008 April. The adopted beta minus decay energy value $Q(\beta)$ = 574 (5) keV is also from 2003Au03.

3.1. Half-life

In the literature, four measured ^{211}Bi half-life ($T_{1/2}$) values are reported. All these measurements are old (the most recent is from 1970), so new half-life measurements are needed to improve the quality of the evaluation. The half-life values and their uncertainties are presented in Table 2.

The value recommended by Curie et al. (1931), with an estimated uncertainty added by the evaluator, was included, too. The uncertainty of other two results (1954Sp32 and 1965Nu03) was also estimated by the evaluator. The set of data is consistent and the recommended value, 2.15 minutes, with an uncertainty of 0.02 minutes, is the weighted average (LWM, χ^2_ν=3.7) of the four input values.

Table 2 : ^{211}Bi Half-life values

$T_{1/2}$ (minutes)	Uncertainty of $T_{1/2}$ (minutes)	Reference
2.16	0.08	1931Cu01
2.15	0.02	1954Sp32
2.13	0.03	1965Nu03
2.22	0.06	1970Mu21

3.2. Alpha and Beta transitions and emissions

In the literature, the most important reference that studies measurements of alpha-particle energies and emission intensities for ^{211}Bi alpha transitions is 1991Ry01.

For this evaluation, the two adopted alpha-particle emission energies were calculated as weighted means of the experimental values presented in Table 3 (both data sets are consistent):

Table 3: Energy of the alpha-particles emitted in the ^{211}Bi decay

Alpha-particle group	Energy of the alpha particles (experimental), keV	Reference
$\alpha_{0,1}$	6300 (10)	1989It01
	6278.2 (7)	1991Ry01
	6279 (1)	1992Sc26
	Recommended energy value: 6278.5 (9) keV	
$\alpha_{0,0}$	6622.9 (6)	1971Gr17 and 1991Ry01
	6620 (10)	1989It01
	6621.33 (69)	1991Ry01
	6623 (1)	1992Sc26
	Recommended energy value: 6622.4 (6) keV	

The ratio of the 6278.5 keV to the sum of 6278.5 keV and 6622.4 keV alpha-particle emission probabilities was determined in a similar way, as the weighted mean of four experimental values reported in the literature and presented below, in Table 4. This data set is discrepant and, consequently, the uncertainty was expanded to include in its range the most precise relative value (16.43 (4) from 1967Da10); the adopted value is 16.20 (23). Considering both the experimental results and the normalization condition (modified to take into account the beta minus decay, see section 2), i.e. the sum of the two absolute alpha-particle emission probabilities must be 100 % - 0.276 (4) % = 99.724 (4) %, the computed absolute emission probability of the 6278.5 keV alpha-particles is 16.16 (23) %. The 6622.4 keV alpha-particles absolute emission probability is then 83.56 (23) %.

The beta minus transition is of the first order forbidden type (non-unique) and populates the ground state of ^{211}Po. The beta particles must have a maximum energy of 574 keV (corresponding to the Q(β) value) and an absolute emission probability of 0.276 (4) %. The adopted values of the average beta minus energy (172.9 (18) keV) and log ft (5.99) were obtained by using the LOGFT computer program.

Table 4: Experimental values of the relative alpha-particles emission probability ratio (6278.5 keV) / (6278.5 keV + 6622.4 keV)

Alpha-particle emission probability ratio (6278.5 keV) / (6278.5 keV + 6622.4 keV) x 100	Reference
15.8 (1)	1962Gi04
15.9 (3)	1962Wa18
16.02 (5)	1966Go13
16.43 (4)	1967Da10

3.3. γ- transitions: γ rays and internal conversion electrons

There is a single gamma-ray transition following the ^{211}Bi decay. Both its energy and emission probability were studied by many scientists. Table 5 summarizes the experimental results published in the literature. The adopted energy of this gamma-ray transition is the weighted mean of the 6 values from Table 5 (consistent data set): 351.03 (4) keV.

The absolute emission probability of this gamma-ray was determined from the alpha feeding of 16.16 (23) % to the ^{207}Tl excited state: 16.16 (23) / 1.243 (4) = 13.00 (19) %, where 0.243 (4) is the total internal conversion coefficient (total ICC), which is in good agreement with the experimental values reported in references 1976Bl13 and 1982Mo30 (see Table 5).

All the internal conversion coefficients (ICCs) adopted in this evaluation were computed with the program BrIcc, version 2.2 /2008, using the “Frozen Orbitals” approximation (2008Ki07). The energy range of the internal conversion electrons corresponding to the gamma-ray transition is from 265.5 keV to 351.02 keV, whereas the total number of conversion electrons emitted per 100 disintegrations is 3.17 (7) (i.e.3.17 (7) %)

Table 5: ^{211}Bi γ-ray Energy and Absolute Emission Probability (experimental values)

E_γ (keV)	Uncertainty E_γ (keV)	Absolute Emission Probability (%)	Uncertainty of absolute emission probability (%)	Reference
351.0	0.1	10.70	0.30	1968Br17
351.0	0.3			1973UrZX
351.01	0.04			1975VaYT
351.07	0.05	12.27	1.4	1976Bl13
351.89	0.20	13.3	1.3	1982Mo30
351.06	0.12			1988Hi14

4. Atomic data

The K-shell fluorescence yield (ω_K), the mean L-shell fluorescence yield (ϖ_L) and the mean number of vacancies in the L-shell produced by one vacancy in the K-shell (η_{KL}) were determined using the computer program EMISSION v.3.10, 28-Jan-2003: 0.963 (4), 0.367 (15) and 0.812 (5) respectively.

4.1. Auger electrons and X-rays

The relative probability values of the K Auger electron emissions (KLL, KLX, KXY) normalized to the KLL value, were computed using the same EMISSION computer program. The total numbers of K and L Auger electrons emitted per disintegration were also calculated (in %): 0.096 (11) and 1.620 (21), respectively. The energy ranges for K and L Auger electrons were filled-in by the SAISINUC program, version 2008 April.

The relative probability (normalized to $K_{\alpha1}$ X-rays emission) and the absolute emission probability values of the different groups of K and L X-rays were determined using the same EMISSION program. The adopted values (in %) of the total absolute emission probability of the KX-rays and LX-rays were 2.50 (6) and 0.931 (19), respectively. The energy range values of the K and L X-rays are from the tables linked to SAISINUC.

Only one reference reporting the measurement of the ^{207}Tl KX-rays energies and emission probabilities was found in the literature (1976Bl13). A comparison between these experimental values and the results of this evaluation is presented in Table 6.

For the two K_α X-rays the results are in very good agreement for energy and unsatisfactory for the absolute emission probability values. The Tl-Kα2 and Tl-Kα1 x-ray absolute emission probabilities reported in 1976Bl13 are about 30 % lower than expected (See Table 6). The cause of this serious disagreement is unknown.

For the two K_β X-rays, the energy values are in good agreement, whereas the absolute emission probabilities values again are in clear disagreement. There are at least two possible causes of this disagreement:

- the evaluated values refer to a sum of three components, not only to $K\beta_1$, respectively $K\beta_2$ (see the Note below Table 6);
- the measurements reported in the article 1976Bl13 include also the Rn $K\alpha_1$ X-rays with an energy of 83.788 keV, situated just between the two components of interest; the presence of this additional peak makes the spectral analysis of this region more difficult, considering the software tools available in 1976 (a higher uncertainty than reported for the experimental results is possible).

This second assumption is supported by the very good agreement between the sum of Tl-$K\beta_1$ and Tl-$K\beta_2$ absolute emission probabilities (in %), according to Table 6: 0.542 (12) (evaluated) and 0.55 (6) (experimental).

Neither measurements of ^{207}Tl LX-rays energies nor of emission probabilities were found in the literature, in order to compare them with the results of this evaluation.

Table 6: Comparison of the evaluated Tl KX-rays energy and absolute emission probability values with experimental results from 1976Bl13

X-rays identification	Evaluated energy (keV)	Evaluated Absolute Emission Probability (in %)	Experimental energy (keV)	Experimental absolute emission probability (in %) (1976Bl13)
Tl-Kα_2	70.832	0.726 (16)	70.839 (13)	0.51 (8)
Tl-Kα_1	72.872	1.225 (27)	72.857 (10)	0.82 (12)
Tl-Kβ_1	82.577	0.417 (11) *	83.019 (80)	0.24 (4)
Tl-Kβ_2	84.838	0.124 (4) *	84.720 (50)	0.31 (4)

* Note: the evaluated absolute emission probabilities of the two K$_\beta$ X-rays include not only the contributions of the Kβ_1 and Kβ_2 components, but also Kβ_3, K''β_5, Kβ_4 and KO$_{2,3}$.

5. Main production mode

The main production mode of ^{211}Bi is by beta minus decay of the ^{211}Pb nuclei (both nuclides are members of the Actinium-Uranium natural radioactive series). ^{211}Bi can be produced also by the alpha decay of ^{215}At (a process of very low probability in the above mentioned radioactive series, because ^{215}At is produced by the weak beta minus decay branch of ^{215}Po, which is about $2.3 \cdot 10^{-4}$ %).

6. References

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