^{215}Bi – Comments on evaluation of decay data
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Evaluation Procedure

Limitation of Relative Statistical Weight Method (LWM) was applied to average numbers throughout the evaluation. The uncertainty assigned to the average value was always greater than or equal to the smallest uncertainty of the values used to calculate the average.

Decay Scheme

The ^{215}Bi ground state (J^π = $(9/2^-)$) decays 100 % by β^- emission to various excited levels and the ground state of ^{215}Po. A reasonably complex but inadequate decay scheme has been constructed primarily from the gamma-ray measurements of Kurpeta *et al.* (2003Ku26) in which 19 distinct gamma-ray emissions were identified with the β^- decay of ^{215}Bi. Although these authors assessed that there is no direct beta decay to the ground state of ^{215}Po, their reported absolute emission probabilities for the gamma rays populating the ground state are in conflict with this proposal.

Direct β^- feeding to the ground state of daughter ^{215}Po has not been satisfactorily determined. Therefore, the evaluators resorted to comparisons with the β^- decay of other odd-even Bi radionuclides (^{213}Bi) and β^--decay theory in order to define the β^- and γ emission probabilities in absolute terms. Further studies are required to clarify and define more clearly the ^{215}Bi decay scheme, particularly with respect to the absolute gamma-ray emission probabilities and quantification of direct β^- feeding to the ground state of daughter ^{215}Po.

Nuclear Data

^{215}Bi is part of the (4n + 3) naturally-occurring decay chain, and of relevance in quantifying the environmental impact of ^{235}U and decay-chain products. Specific radionuclides in this decay chain are noteworthy because of their decay characteristics (^{215}Po, ^{211}Bi and ^{211}Po alpha decay).

Half-life

^{215}Bi was first observed by 1953Hy83, and assigned a half-life of (8 ± 2) min. However, the recommended half-life is the weighted mean of three more recent measurements (1965Nu03, 1989Bu09 and 1990Ru02).

Reference	Half-life (min)
1965Nu03	7.4 (6)
1989Bu09	7.5 (4)
1990Ru02	7.7 (2)
Recommended value	7.6 (2)

^{215}Po half-life of 1.781 (4) millisecond was adopted from the evaluation of Browne (2001Br31).

Q value

Q^- of 2189 (15) keV was adopted from the evaluated tabulations of Audi *et al.* (2003Au03).

Beta particles

Energies

All beta-particle energies were calculated from the structural details of the proposed decay scheme. A combination of nuclear level energies recommended by 2001Br31 and derived from 2003Ku26, and a Q-value of 2189 (15) keV (2003Au03) were used to determine the energies and uncertainties of the beta-particle emissions to the various levels.

Adopted nuclear levels of ^{215}Po: Energy, J^{π} and origins (2001Br31, 2003Ku26).

Nuclear level	Nuclear level energy (keV)	J^{π}	Origins
0	0.0	9/2 +	**^{215}Bi β^- decay**, ^{219}Rn α decay
1	271.228 ± 0.010	7/2 +	**^{215}Bi β^- decay**, ^{219}Rn α decay
2	293.56 ± 0.04	11/2 +	**^{215}Bi β^- decay**, ^{219}Rn α decay
3	401.812 ± 0.010	5/2 +	**^{215}Bi β^- decay**, ^{219}Rn α decay
4	517.60 ± 0.06	7/2 +, 9/2 +	**^{215}Bi β^- decay**, ^{219}Rn α decay
5	608.30 ± 0.07	(11/2 +, 13/2 +)	**^{215}Bi β^- decay**, ^{219}Rn α decay
6	676.66 ± 0.07		**^{215}Bi β^- decay**, ^{219}Rn α decay
7	708.1 ± 0.5		^{219}Rn α decay
8	732.7 ± 0.4		^{219}Rn α decay
9	835.32 ± 0.22		**^{215}Bi β^- decay**, ^{219}Rn α decay
10	877.2 ± 0.6		^{219}Rn α decay
11	891.1 ± 0.3		^{219}Rn α decay
12	930 ± 1		^{219}Rn α decay
13	1073.7 ± 0.4	(5/2 +)	^{219}Rn α decay
14	1077.6 ± 2.0*		**^{215}Bi β^- decay**
15	1094.2 ± 1.0		^{219}Rn α decay
16	1176.2 ± 2.0*		**^{215}Bi β^- decay**
17	1294.5 ± 0.1*		**^{215}Bi β^- decay**
18	1398.8 ± 0.4*		**^{215}Bi β^- decay**

* Calculated from the energies of the depopulating gamma rays (2003Ku26), and the lower-energy nuclear levels that they populate.

Emission Probabilities

Direct beta-particle feeding to the ground state of ^{215}Po has not been unambiguously defined from the various γ-ray measurements. Under these circumstances, a systematic assessment of the appropriate properties of odd-even Bi nuclides in the vicinity of ^{215}Bi has been undertaken to explore whether a reasonable approximation can be made of beta decay directly to the ground state of ^{215}Po (1991Ma16, 2001Br31, 2003Ak06, 2004Br45, 2007Ba19).

(a) Spin and parity of ^{215}Bi

Nuclide	^{209}Bi	^{211}Bi	^{213}Bi	^{215}Bi	^{217}Bi
β^- decay	stable	0.28 %	97.91 %	100 %	100 %
Direct β^- decay to ground state	–	0.28 %	65.9 %	?	?
α decay	stable	99.72 %	2.09 %	–	–
Spin and parity	$9/2^-$	$9/2^-$	$9/2^-$	$(9/2^-)$	?
Spin and parity of Po ground state	$1/2^-$	$9/2^+$	$9/2^+$	$9/2^+$	$(11/2^+)$

Spins and parities of $9/2^-$ are well defined for ^{209,211,213}Bi, and can be similarly assigned with reasonable confidence as $(9/2^-)$ for ^{215}Bi.

(b) Direct beta-particle feeding of ^{215}Bi to the ground state of ^{215}Po

Population-depopulation balances have been calculated on the basis of the relative emission probabilities of the gamma rays (see below) in order to derive relative beta-particle emission probabilities to all of the excited nuclear levels of ^{215}Po.

The β^- decay of ^{215}Bi was assumed to occur primarily via first forbidden non-unique transitions to the ground state ($9/2^+$) and 293.56-keV nuclear level ($11/2^+$) of ^{215}Po. The preparation of recommended decay-data files for DDEP necessitates the formulation of decay schemes that are based on absolute emission and transition probabilities that frequently encompass well-defined normalization factors in conjunction with accurate relative emission probabilities and various other nuclear parameters (e.g. internal conversion coefficients). This ideal situation cannot be achieved for ^{215}Bi because of existing inadequacies in the measured data. Therefore, the main β^- branches populate the 293.56-keV nuclear level and ground state of ^{215}Po, and their important emission probabilities have been derived somewhat unusually through application of the fifth-power law of β^- decay (1933Sa01, 1955Ev23, 1963KaZZ).

A general approximation has been formulated for the ratio of allowed beta-particle emission probabilities, based on the observation that the mean life (τ) for partial β^- decay is inversely proportional to the fifth power of the β^- end-point energy (1955Ev23, 1963KaZZ):

$$\frac{1}{\tau_\beta} \propto [(M(Z) - M(Z \pm 1)c^2)]^5$$

where

$$\tau_\beta = \frac{\tau_{exp}}{P_\beta} \quad \text{and} \quad \tau_{exp} \text{ is the lifetime of the parent nuclide.}$$

Therefore

$$\frac{1}{\tau_\beta} \sim (E_\beta)^5$$

This approximation has been applied to the major first-forbidden non-unique beta-particle emissions of ^{215}Bi directly to the ground state of ^{215}Po ($(9/2^-) \rightarrow 9/2^+$)

$$\frac{1}{\tau_{0,0}} \sim (E_{\beta_{0,0}})^5 \qquad (1)$$

and to the 293.56-keV nuclear level of ^{215}Po ($(9/2^-) \rightarrow 11/2^+$)

$$\frac{1}{\tau_{0,2}} \sim (E_{\beta_{0,2}})^5 \qquad (2)$$

Combining equations (1) and (2):

$$\frac{\tau_{0,2}}{\tau_{0,0}} = \frac{P_{\beta_{0,0}}}{P_{\beta_{0,2}}} \sim \left(\frac{E_{\beta_{0,0}}}{E_{\beta_{0,2}}}\right)^5 = \left[\frac{2189(15)}{1895(15)}\right]^5 = 1.155^5 \sim 2.055$$

where $P_{\beta_{0,0}}$ and $P_{\beta_{0,2}}$ are the β-particle emission probabilities to the ground state and 293.56-keV nuclear level, respectively.

The proposed decay scheme, recommended relative emission probabilities of the gamma rays and α_{total} have been used to determine a $P^{rel}_{\beta_{0,2}}$ value of 125 (7) by the appropriate summation of the measured gamma population/depopulation of the 293.56-keV nuclear level. Therefore:

$$P^{rel}_{\beta_{0,0}} \sim 2.055 \times 125\,(7) = 257\,(14)$$

with an uncertainty assigned in a somewhat arbitrary manner on the basis of the uncertainty derived for $P^{rel}_{\beta_{0,2}}$.

The normalization factor (*NF*) for the relative emission probabilities of both the β^- particles and γ rays has been determined from the total $\beta\gamma$ transitions populating the ground state of ^{215}Po directly:

$$P^{rel}_{\beta_{0,0}} \times NF + \sum P^{rel}_{\gamma}(1 + \alpha_{total}) \times NF = 100$$

$$257\,(14) \times NF + [164\,(7) \times NF] = 100$$

$$NF = 100/421\,(16) = 0.238\,(9)$$

Both P^{abs}_{β} to the ground state and 293.56-keV nuclear level of ^{215}Po were simply calculated from their P^{rel}_{β} values and *NF*, and are coupled together on the basis of crude estimates of their uncertainties (i.e. arbitrary uncertainty of 20 % assigned to the value of $P_{\beta^-_{0,2}}$):

$P^{abs}_{\beta_{0,2}}$ of 30 (6) %

and $P^{abs}_{\beta_{0,0}}$ of 61 (6) %.

These data should be treated with a high degree of caution. Their derivation also impacts significantly on the quantification of the other beta-particle emission probabilities.

Apart from the beta-particle emission directly to the ground state of ^{215}Po, the relative emission probabilities of all of the other beta-particle decays were calculated from population-depopulation balances of the relative gamma transition probabilities, as derived from the relative gamma-ray emission probabilities and internal conversion coefficients determined from the frozen orbital approximation of Kibédi *et al*. (2008Ki07) based on the theoretical model of Band *et al*. (2002Ba85, 2002Ra45). Direct beta population of the 271.228-keV nuclear level of ^{215}Po was calculated to be zero from the calculation of the known gamma transition probabilities populating and depopulating this particular excited state ((9/2$^-$) to 7/2$^+$ (1st forbidden non-unique)).

Beta-particle emission probabilities per 100 disintegrations of ^{215}Bi, transition type and log *ft*.

$E_β$(keV)	$P_β$ Recommended value	transition type‡	log *ft*#
790 (15)	2.8 (1)*	[1st forbidden non-unique]	6.00
895 (15)	2.0 (2)*	[1st forbidden non-unique]	6.34
1013 (15)	0.2 (1)*	[1st forbidden non-unique]	7.5
1111 (15)	0.7 (1)*	[1st forbidden non-unique]	7.1
1354 (15)	1.5 (1)*	[1st forbidden non-unique]	7.10
1512 (15)	0.5 (1)*	[1st forbidden non-unique]	7.8
1581 (15)	0.7 (1)*	(1st forbidden non-unique)	7.7
1671 (15)	0.3 (2)*	(1st forbidden non-unique)	8.1
1787 (15)	0.5 (1)*	(1st forbidden unique)	9.0
1895 (15)	30 (6) *†	(1st forbidden non-unique)	6.35
1918 (15)	–	(1st forbidden non-unique)	–
2189 (15)	61 (6)†	(1st forbidden non-unique)	6.28
	Σ 100 (8)		

* Recommended absolute $β^-$ emission probabilities derived from the relative gamma-ray emission probabilities, normalization factor of 0.238 (9), and theoretical internal conversion coefficients.
† Absolute emission probabilities calculated from fifth-power relationship of $β^-$ end-point energies, with an arbitrary estimated uncertainty of 20 % assigned to the 1895-keV $β^-$ emission probability.
‡ Transition types within square brackets [] are not based on any spin-parity assignments – they have been assumed to be first forbidden non-unique as observed for the majority of the higher-energy $β^-$ transitions.
\# Log *ft* values calculated on the assumption of first forbidden non-unique transitions, apart from the 1787-keV beta emission (defined as most likely to be first forbidden unique).

The observed systematics of the two principle emissions in $β^-$ decay for odd-even nuclides has been used in a quantitative manner to derive beta-particle emission probabilities in absolute terms. This approach is both approximate and of highly questionable merit – under these unsatisfactory circumstances, further experimental studies are required to determine direct $β^-$ feeding to the ground state of daughter ^{215}Po with good accuracy.

Gamma rays

Energies

All gamma-ray transition energies were calculated from the structural details of the proposed decay scheme derived from 2001Br31 and 2003Ku26. The lower-energy nuclear level energies of 2001Br31 were adopted, along with higher-energy nuclear levels calculated from the gamma-ray studies of 2003Ku26. These data were subsequently used to re-determine the energies and associated uncertainties of the gamma-ray transitions between the various populated-depopulated levels.

Emission Probabilities

The only known experimental studies of relevance in defining the decay scheme of ^{215}Bi are the measurements by Ruchowska *et al.* (1990Ru02) in which the emission probabilities of seven gamma-ray transitions were quantified in terms of Pγ(293.56 keV) of 1000 (redefined as 100 %), and the more extensive studies of Kurpeta *et al.* (2003Ku26) in which the emission probabilities of 19 gamma-ray transitions were quantified.

Table 3 and Fig. 6 of 2003Ku26 contain highly questionable absolute β-particle and γ-ray emission probabilities. While the resulting γ-ray transition probabilities populating the ^{215}Po ground state directly sum to only 57.6 %, no direct $β^-$ decay is advocated to achieve a correct summation of 100 %. Private communications between Kurpeta (Institute of Experimental Physics, Warsaw University) and Kondev (ANL), April 2011, have clarified the caption of Table 3: γ intensities listed in this table are relative and not absolute (defined erroneously as %

per decay). Therefore, these γ-ray emission probabilities have been re-defined as relative to Pγ(293.56 keV) of 100 %.

A number of unobserved low-intensity gamma rays have also been introduced by considering the equivalent gamma-ray studies of the α decay of ^{219}Rn – this process results in the introduction of the 130.58-, 224.04- and 405.43-keV gamma transitions, each with relative emission probabilities of less than 0.15 %.

Gamma-ray emission probabilities: as published, and relative to P_γ(293.56 keV) of 100 %.

E_γ (keV)	P_γ^{rel}			
	1990Ru02	2003Ku26† as published	adjusted	Recommended value*
130.58 (1)	–	–	–	0.039(4)‡
224.04 (7)	–	–	–	0.14 (2)‡
271.228 (10)	5.5 (5)	2.9 (1)	8.2 (3)	8.2 (3)
293.56 (4)	100 (7)	35.2 (11)	100 (3)	100 (3)
383.10 (8)	–	0.2 (1)	0.6 (3)	0.6 (3)
401.81 (1)	1.0 (4)	0.7 (1)	2.0 (3)	2.0 (3)
405.43 (7)	–	–	–	0.024 (4)‡
517.60 (6)	1.9 (3)	1.5 (1)	4.3 (3)	4.3 (3)
541.76 (22)	–	0.3 (1)	0.9 (3)	0.9 (3)
564.09 (22)	1.3 (3)	1.0 (1)	2.8 (3)	2.8 (3)
608.30 (7)	–	1.0 (1)	2.8 (3)	2.8 (3)
676.66 (7)	0.6 (2)	0.6 (1)	1.7 (3)	1.7 (3)
776.9 (1)	–	1.2 (2)	3.4 (6)	3.4 (6)
784 (2)	–	0.5 (1)	1.4 (3)	1.4 (3)
806.4 (20)	–	0.6 (1)	1.7 (3)	1.7 (3)
835.32 (22)	1.4 (3)	0.9 (1)	2.6 (3)	2.6 (3)
905 (2)	–	0.3 (1)	0.9 (3)	0.9 (3)
1023.3 (1)	–	0.9 (1)	2.6 (3)	2.6 (3)
1105.2 (4)	–	2.2 (1)	6.3 (3)	6.3 (3)
1127.6 (4)	–	0.7 (1)	2.0 (3)	2.0 (3)
1294.5 (1)	–	0.9 (1)	2.6 (3)	2.6 (3)
1398.8 (4)	–	1.2 (1)	3.4 (3)	3.4 (3)

† Published as absolute emission probabilities of doubtful overall pedigree (transition probabilities directly populating the ^{215}Po ground state only sum to 57.6 %, while direct β^- decay of zero is advocated); J. Kurpeta (Institute of Experimental Physics, Warsaw University), private communication to F.G. Kondev (ANL), 27 April 2011, concerning caption of Table 3 (2003Ku26): γ intensities are relative and not % per decay – therefore, emission probabilities have been adjusted to be relative to Pγ(293.56 keV) of 100 %.

* Recommended data biased completely towards the more extensive measurements of 2003Ku26.

‡ Derived from equivalent γ-ray measurements of ^{219}Rn α decay.

Major disagreements are observed between the emission probability measurements of 1990Ru02 and 2003Ku26 that negate the merit of any form of weighted-mean analysis. Under these circumstances, the more comprehensive data of 2003Ku26 have been adopted relative to Pγ(293.56 keV) of 100 %.

Multipolarities and Internal Conversion Coefficients

The decay scheme specified by 2001Br31 has been used to define the multipolarity of specific gamma transitions on the basis of the known spins and parities of the nuclear levels. Thus, the 224.04- and 401.81-keV gamma-ray emissions are adjudged to be E2 transitions. Multipolarity mixing ratios for the 130.58- and 271.228-keV gamma transitions of 0.60 (6) and 4.0 (4), respectively, were derived from the K/L and L sub-shell conversion-electron ratios determined by Davidson and Connor (1970Da09), while the 293.56- and 517.60-keV gamma-ray emissions were arbitrarily assigned mixing ratios of 1.0 (2) (i.e. 50 % M1 + 50 % E2). Recommended internal conversion coefficients have been determined from the frozen orbital approximation of Kibédi *et al*. (2008Ki07), based on the theoretical model of Band *et al*. (2002Ba85, 2002Ra45).

Gamma-ray emissions: multipolarities and theoretical internal conversion coefficients (frozen orbital approximation).

E_γ (keV)	Multipolarity	α_K	α_L	α_{M+}	α_{total}
130.58 (1)	73.5%M1 + 26.5%E2 δ = 0.60(6)	3.19 (16)	0.94 (4)	0.31	4.44 (13)
224.04 (7)	(E2)	0.1296 (19)	0.1407 (20)	0.0487	0.319 (5)
271.228 (10)	6%M1 + 94%E2 δ = 4.0(4)	0.111 (6)	0.0668 (11)	0.0232	0.201 (7)
293.56 (4)	(50%M1 + 50%E2) δ = 1.0(2)	0.25 (4)	0.062 (4)	0.028	0.34 (5)
383.10 (8)	–	–	–	–	–
401.81 (1)	E2	0.0351 (5)	0.01528 (22)	0.00512	0.0555 (8)
405.43 (7)	–	–	–	–	–
517.60 (6)	50%M1 + 50%E2 δ = 1.0(2)	0.058 (9)	0.0115 (11)	0.0035	0.073 (10)
541.76 (22)	–	–	–	–	–
564.09 (22)	–	–	–	–	–
608.30 (7)	(M1 + E2)	–	–	–	–
676.66 (7)	–	–	–	–	–
776.9 (1)	–	–	–	–	–
784 (2)	–	–	–	–	–
806.4 (20)	–	–	–	–	–
835.32 (22)	–	–	–	–	–
905 (2)	–	–	–	–	–
1023.3 (1)	–	–	–	–	–
1105.2 (4)	–	–	–	–	–
1127.6 (4)	–	–	–	–	–
1294.5 (1)	–	–	–	–	–
1398.8 (4)	–	–	–	–	–

While a decay scheme has been formulated from the gamma-ray emission probability measurements of Kurpeta *et al.* (2003Ku26), further studies are required to determine the absolute and relative gamma-ray emission probabilities and also quantify any direct β^- feeding to the ground state of daughter ^{215}Po with much greater confidence. Such work would assist greatly to remove the severe doubts associated with the proposed decay scheme.

Atomic Data

The x-ray data have been calculated using the evaluated gamma-ray data, and the atomic data from 1996Sc06, 1998ScZM and 1999ScZX. Both the x-ray and Auger-electron emission probabilities were determined by means of the EMISSION computer program (version 4.01, 28 January 2003). This program incorporates atomic data from 1996Sc06 and the evaluated gamma-ray data.

K and L X-ray emission probabilities per 100 disintegrations of ^{215}Bi.

			Energy (keV)	Photons per 100 disint.
XL		(Po)	9.658 – 16.213	2.7 (3)
	XL_l	(Po)	9.658	0.065 (8)
	XL_α	(Po)	11.016 – 11.130	1.20 (13)
	XL_η	(Po)	12.085	0.022 (3)
	XL_β	(Po)	12.823 – 13.778	1.18 (11)
	XL_γ	(Po)	15.742 – 16.213	0.24 (2)
XK_α	$XK_{\alpha2}$	(Po)	76.864 (4)	1.8 (3)
	$XK_{\alpha1}$	(Po)	79.293 (5)	3.0 (5)
$XK'_{\beta1}$	$XK_{\beta3}$	(Po)	89.256	)
	$XK_{\beta1}$	(Po)	89.807	) 1.02 (16)
	$XK'_{\beta5}$	(Po)	90.363	)
$XK'_{\beta2}$	$XK_{\beta2}$	(Po)	92.263	)
	$XK_{\beta4}$	(Po)	92.618	) 0.32 (5)
	$XKO_{2,3}$	(Po)	92.983	)

Electron energies were determined from electron binding energies tabulated by Larkins (1977La19) and the evaluated gamma-ray energies. Absolute electron emission probabilities were calculated from the evaluated absolute gamma-ray emission probabilities and associated internal conversion coefficients.

Data Consistency

A Q_β-value of 2189 (15) keV has been adopted from the atomic mass evaluation of Audi *et al.* (2003Au03) while in the course of formulating the decay scheme of ^{215}Bi. This value has subsequently been compared with the Q-value calculated by summing the contributions of the individual emissions to the ^{215}Bi beta-decay process (i.e. β^-, conversion electrons, γ, etc.):

$$\text{calculated Q-value} = \sum (E_i \times P_i) = 2190\ (170)\ \text{keV}$$

Percentage deviation from the Q-value of Audi *et al.* is (0 ± 8) %, which supports the derivation of a highly consistent decay scheme with a large variant.

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