

**²¹⁵Bi – 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 ²¹⁵Bi ground state ($J^\pi = (9/2^-)$) decays 100 % by β^- emission to various excited levels and the ground state of ²¹⁵Po. 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 ²¹⁵Bi. Although these authors assessed that there is no direct beta decay to the ground state of ²¹⁵Po, 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 ²¹⁵Po has not been satisfactorily determined. Therefore, the evaluators resorted to comparisons with the β^- decay of other odd-even Bi radionuclides (²¹³Bi) 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 ²¹⁵Bi decay scheme, particularly with respect to the absolute gamma-ray emission probabilities and quantification of direct β^- feeding to the ground state of daughter ²¹⁵Po.

Nuclear Data

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

Half-life

²¹⁵Bi 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)

²¹⁵Po 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 particlesEnergies

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 ²¹⁵Po: 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 ²¹⁵Po 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 ²¹⁵Bi has been undertaken to explore whether a reasonable approximation can be made of beta decay directly to the ground state of ²¹⁵Po (1991Ma16, 2001Br31, 2003Ak06, 2004Br45, 2007Ba19).

(a) Spin and parity of ²¹⁵Bi

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 ²¹⁵Bi.

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

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 ²¹⁵Po.

The β⁻ decay of ²¹⁵Bi 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 ²¹⁵Po. 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 ²¹⁵Bi because of existing inadequacies in the measured data. Therefore, the main β⁻ branches populate the 293.56-keV nuclear level and ground state of ²¹⁵Po, 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 ²¹⁵Bi directly to the ground state of ²¹⁵Po ((9/2⁻) → 9/2⁺)

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

and to the 293.56-keV nuclear level of ²¹⁵Po ((9/2⁻) → 11/2⁺)

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

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 $P_{\beta_{0,2}}^{rel}$ value of 125 (7) by the appropriate summation of the measured gamma population/depopulation of the 293.56-keV nuclear level. Therefore:

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

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

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 ²¹⁵Po directly:

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

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

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

Both P_{β}^{abs} to the ground state and 293.56-keV nuclear level of ²¹⁵Po were simply calculated from their P_{β}^{rel} 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 $P_{\beta_{0,2}}^-$):

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

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

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 ²¹⁵Po, 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 ²¹⁵Po 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 ²¹⁵Bi, transition type and log *ft*.

E_{β} (keV)	P_{β}	transition type [‡]	log <i>ft</i> [#]
	Recommended value		
790 (15)	2.8 (1) [*]	[1 st forbidden non-unique]	6.00
895 (15)	2.0 (2) [*]	[1 st forbidden non-unique]	6.34
1013 (15)	0.2 (1) [*]	[1 st forbidden non-unique]	7.5
1111 (15)	0.7 (1) [*]	[1 st forbidden non-unique]	7.1
1354 (15)	1.5 (1) [*]	[1 st forbidden non-unique]	7.10
1512 (15)	0.5 (1) [*]	[1 st forbidden non-unique]	7.8
1581 (15)	0.7 (1) [*]	(1 st forbidden non-unique)	7.7
1671 (15)	0.3 (2) [*]	(1 st forbidden non-unique)	8.1
1787 (15)	0.5 (1) [*]	(1 st forbidden unique)	9.0
1895 (15)	30 (6) ^{*†}	(1 st forbidden non-unique)	6.35
1918 (15)	–	(1 st forbidden non-unique)	–
2189 (15)	61 (6) [†]	(1 st 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 ²¹⁵Po with good accuracy.

Gamma rays

Energies

All gamma-ray transition energies were calculated from the structural details of the proposed decay scheme derived from 2001Br01 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 ²¹⁵Bi are the measurements by Ruchowska *et al.* (1990Ru02) in which the emission probabilities of seven gamma-ray transitions were quantified in terms of $P_{\gamma}(293.56 \text{ keV})$ 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 ²¹⁵Po 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 $P_{\gamma}(293.56 \text{ keV})$ 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 $P_{\gamma}(293.56 \text{ keV})$ of 100 %.

E_{γ} (keV)	P_{γ}^{rel}			Recommended value*
	1990Ru02	2003Ku26 [†] as published	adjusted	
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 $P_{\gamma}(293.56 \text{ keV})$ 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 $P_{\gamma}(293.56 \text{ keV})$ 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 $\delta = 0.60(6)$	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 $\delta = 4.0(4)$	0.111 (6)	0.0668 (11)	0.0232	0.201 (7)
293.56 (4)	(50%M1 + 50%E2) $\delta = 1.0(2)$	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 $\delta = 1.0(2)$	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 ²¹⁵Po 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 ²¹⁵Bi.

			Energy (keV)	Photons per 100 disint.
XL		(Po)	9.658 – 16.213	2.7 (3)
	XL ₁	(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 _{α2}	(Po)	76.864 (4)	1.8 (3)
	XK _{α1}	(Po)	79.293 (5)	3.0 (5)
XK' _{β1}	XK _{β3}	(Po)	89.256)
	XK _{β1}	(Po)	89.807) 1.02 (16)
	XK _{β5}	(Po)	90.363)
XK' _{β2}	XK _{β2}	(Po)	92.263)
	XK _{β4}	(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 ²¹⁵Bi. This value has subsequently been compared with the Q-value calculated by summing the contributions of the individual emissions to the ²¹⁵Bi 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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