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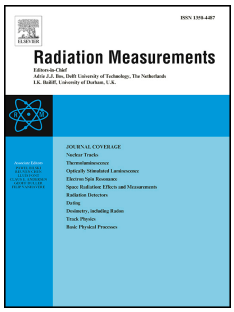

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PII: S1350-4487(17)30821-1

DOI: 10.1016/j.radmeas.2018.02.007

Reference: RM 5877

To appear in: *Radiation Measurements*

Received Date: 6 December 2017

Revised Date: 26 February 2018

Accepted Date: 26 February 2018

Please cite this article as:

Dose Rate Conversion Parameters: Assessment of Nuclear Data

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Abstract

The dating of materials using stored dose methods requires accurate determination of the environmental dose rate. The calculation of dose rates from radionuclide concentrations requires conversion parameters derived from nuclear data (half life, decay energies and intensities, and branching ratios). With the substantial body of primary data, it is convenient to use data from evaluated libraries. These libraries show variations reflecting both newer data unavailable to earlier evaluations and the relative importance given to different data sets by the evaluators. Commonly used conversion parameters derive from the Evaluated Nuclear Structure Data File (ENSDF), either directly or from secondary publications, with new tabulations produced in recent years following revisions to this library. Other international evaluations of nuclear data include the NEA/OECD supported JEF2.2 and JEFF3.11 evaluations, and the Decay Data Evaluation Project (DDEP). A technique comparing different evaluations to identify data that can not be confidently used has been developed. These differences have been investigated with an evaluation of underlying nuclear data. Particular radionuclides of interest are discussed; ^{214}Bi where recent evaluations depend on a single high precision data set, ^{228}Ac where the decay scheme is incomplete and further measurements are required, and ^{40}K where the mean beta energy has been calculated in the evaluations using an incorrect shape factor. Revised dose rate conversion factors have been

produced, which are largely consistent with earlier values with the exception of the ^{40}K beta parameter which is 4% higher than recent values but consistent with earlier calculations.

Keywords

Dose rate conversion factors; evaluated nuclear data; 214Bi; 228Ac; 40K

Research Highlights

- Innovative comparison of evaluated libraries to highlight lower confidence data
- Highlighted radionuclides with lowest confidence data - 214Bi, 228Ac, 40K
- 40K beta spectrum incorrect in all evaluated libraries, improved mean energy given
- Revised dose rate conversion factors using best available data given

1. Introduction

In luminescence or electron-spin resonance dating the age of a mineral is determined from the ratio of the measured equivalent dose to the environmental dose rate the mineral had been exposed to, including appropriate corrections for grain size and water content. In some instances dose rates can be measured directly, using in-situ spectrometers or dosimeters, but in many cases dose rates calculated from measurements of the activity concentration (Bq kg^{-1}) or elemental concentrations (% or ppm) of natural radionuclides, or alpha and beta counting rates, in samples returned to the laboratory for analysis are needed in the absence of field measurements or to supplement other measurements. This calculation uses dose rate conversion factors derived from nuclear data. The calibration of field instruments and dosimeters often also relies on appropriate conversion factors.

These conversion factors have been calculated several times since the 1970's, following revisions to the nuclear data used, as shown in Fig. 1. The values for these parameters are tabulated in the supplementary material. These show some significant variation, but with recent estimates converging on a common value within a few % uncertainty. Nevertheless, comparisons between dose rates determined by different methods and institutions continue to show discrepancies, with the conversion factors used being one potential explanatory factor. Therefore, there is reason to examine these conversion factors again. As the nuclear data used to determine these factors is updated, it could be asked whether it is necessary to update the conversion factors? Or, has the point been reached where those updates will not lead to significant changes in the conversion factors? And, to what extent can we be confident in the nuclear data used? It would be beneficial if variations in nuclear data had been settled to values that are very unlikely to change significantly with further measurement, from which the stored dose dating community could derive an agreed set of conversion factors. It is the aim of this work to examine whether this point has been reached, and if not what is needed to move closer to that position.

The nuclear data required for these calculations are the energies and intensities of discrete radiation (alpha, gamma and x-ray) and the intensities and mean energies of beta radiation, which requires both the decay endpoint and shape of the beta spectrum. When nuclide concentrations are expressed as elemental concentrations (ppm or %) then the half lives of the decays are also required.

2. Nuclear Data Tables

With the very large quantity of nuclear data available, and the specialist nature of many publications, it is often impractical to assimilate the primary data, and it is therefore convenient to refer to evaluated libraries. In this work, three such libraries are considered.

The Evaluated Nuclear Structure Data File (ENSDF) was the first comprehensive nuclear structure data base, developed by staff at Berkeley and Oak Ridge in the late 1970s while the 7th Edition of the *Table of Isotopes* was being compiled, with the first version of the data base largely mirroring the *Table of Isotopes* 7th Edition. The ENSDF consortium developed, and an international network of evaluators was established under the IAEA. The ENSDF database is maintained by the US National Nuclear Data Center at Brookhaven National Laboratory (NNDC, 2017). The database is under constant development, with updated publication of evaluated data in *Nuclear Data Sheets* at a rate of approximately every 7-11 years. The 8th Edition of the *Table of Isotopes* was produced using ENSDF data.

The NEA and OECD coordinated evaluation projects with particular emphasis on nuclear data relevant to reactor physics, which for decay data produced two evaluated libraries, the Joint Evaluated File Version 2.2 (JEF2.2) in 1993 (NEA 2000) and Joint Evaluated Fission and Fusion File Version 3.1.1 (JEFF 3.1.1) in 2007 (Kellett et.al. 2009). Both of these data bases are fixed, without ongoing development and revision.

It has been noted (Helmer 1999) that a significant limitation on many evaluated libraries is the lack of comments on the origin of the data and processing done, making it impossible for others to judge the quality of the evaluations, and that values for quantities differ between evaluated libraries. To address these concerns the Decay Data Evaluation Project (DDEP) was initiated in 1995 (Helmer 1999, Helmer et.al. 2002) with the intention of giving the most

precise values that are justified, with a methodology that includes accounting for all measurements of a quantity (either using or explicitly excluding each measurement), providing written documentation of all the data used and the decisions made, and for each evaluation to be reviewed by other members of the DDEP.

For luminescence dating, dose rate conversion factors were calculated in the 1970s and 80s (Aitken 1974, 1983, Bell 1976, Sanderson 1987 and others) using various editions of the *Table of Isotopes* and *Nuclear Data Sheets*. Several recent re-evaluations use ENSDF data (Adamiec & Aitken 1998, Guerin et.al. 2011, Liritzis et.al. 2013), without any apparent detailed consideration of the basis for the revisions to the evaluated library. As noted, these conversion factors have converged to common values within a few percent. However, they have all been determined from different generations of the same group of evaluations, and any variations using different evaluation procedures would result in a reduction in confidence in these parameters.

The purpose of this paper is to examine the different evaluated nuclear data libraries for the radionuclides of relevance to dosimetry from natural sources: the decay chains from ^{238}U, ^{235}U and ^{232}Th, and the decays of ^{40}K and ^{87}Rb. This will identify the individual radionuclides where there is significant variability in the evaluated nuclear data, or where the uncertainties are larger, which result in the most significant uncertainty in dose rate conversion factors. From this examination, further details of existing data for those radionuclides identified as most significant are given. The influence of these variations on dose rate conversion factors for the infinite matrix condition are then described.

3. Examination of evaluated data for naturally occurring radionuclides

The data in the JEF2.2, JEFF3.11, ENSDF and DDEP libraries were interrogated to tabulate values for the half lives, mean decay energies and intensities, and where appropriate branching ratios, for all naturally occurring radionuclides. This data was tabulated for alpha, beta and gamma decay, x-rays and conversion electrons. These tables, with a more extensive discussion of the nuclear data, are given elsewhere (Cresswell et.al. 2018). Data were downloaded from the ENSDF and DDEP libraries in March 2017. These values have been used to calculate dose rate conversion factors for each of these evaluations, as shown in Fig. 2 and tabulated in the supplementary material.

For the uranium series both ENSDF and DDEP generate significantly lower gamma conversion factors and higher beta conversion factors compared to JEF2.2/JEFF3.1.1. These are driven by data for ^{214}Bi, with significant differences for both beta and gamma mean energies between the evaluated libraries (Table 1) accounting for approximately 1.5% of the total beta and 3.5% of the total gamma energies. The end-point energies, shapes and intensities of beta decays to excited levels in ^{214}Po are determined from analysis of the gamma ray emission spectra. Thus differences in the evaluation of the gamma emission data will account for differences in both the gamma and beta energies.

The evaluation of the gamma decay scheme involves normalising available gamma spectrometry data to the 609 keV (1st excited state to ground state) transition, to allow the generation of a relative intensity level scheme. This is then normalised to an evaluated absolute intensity for the 609 keV transition. The absolute intensities for the 609 keV emission in the ENSDF and DDEP libraries are identical (45.49 ± 0.19%), whereas the

intensity in the JEF2.2/JEFF3.11 library is higher (46.9 ± 4.0%). The JEF2.2 evaluation for ^{214}Bi was not revised in the JEFF3.11 evaluation, and the ENSDF and DDEP libraries include two measurements not available to the JEF2.2 evaluators. In particular, a high precision data set reported by Morel et.al. (2004) using ^{226}Ra sources certified to 0.2% precision, and 4 different HPGe detectors and 2 or 3 source geometries for each detector to check cascade summing correction, with an absolute intensity for the 609 keV gamma ray of 45.57 ± 0.18%. To date, this dataset is the most precise measurement of the critical 609 keV absolute intensity, and the relative intensities of the other emissions from ^{214}Bi decay. To tie down this critical intensity more conclusively there would be value in independent measurements with similar attention to detail to rule out potential bias in the source activity certification, detector efficiencies and cascade summing corrections.

For the thorium series, the ENSDF and DDEP libraries produce lower gamma dose rate conversion factors, with significantly improved precision, compared to JEF2.2 and JEFF 3.11. This is largely explained by differences in the ^{228}Ac decay data (Table 2). Even with more recent data improving the precision of the evaluation, the DDEP evaluation (Pearce 2010) notes that this decay scheme is incomplete. The effective Q-value[1] calculated from individual decay rates and intensities (2010 ± 100 keV) is low compared to the Q-value from mass differences (2123.8 ± 2.7 keV). There is a ~7% discrepancy between beta and gamma emissions, suggesting missing gammas. “Further measurements of the gamma data, particularly at low energy, would be of benefit, as would coincidence studies to validate the placement of gammas in the level scheme” (Pearce 2010). Absolute gamma emissions were normalised to the 463 keV emission, however it is noted that “this value is not consistent with expected beta decay characteristics” (Pearce 2010). If the discrepancies in the decay scheme

[1] The Q-value is the difference in rest mass energy of the parent and daughter nuclides. This should equal the total energy released in the decay (the sum of all radiation and nuclear recoil).

174 are the result of unobserved gamma rays, with associated beta transitions, then it is expected
175 that total gamma and beta energies per decay would be larger than determined from the
176 ENSDF/DDEP libraries by a few percent.
177
178 For ^{40}K the half lives given in the evaluated libraries (Table 3) considered here carry
179 relatively large uncertainties, of 1.0-1.5% for the JEF2.2 and JEFF3.11 libraries, and 0.2% for
180 the ENSDF and DDEP libraries. In addition, the half lives vary significantly with the JEF2.2
181 value approximately 2.5% larger than that given in the ENSDF and DDEP libraries. This
182 difference in half life is significant when ^{40}K activity is given in terms of elemental
183 composition (%K). In geochronology based on the decay of ^{40}K it is desirable to know the
184 ^{40}K to the greatest possible precision. Given the importance of the ^{40}K decay constants in
185 these communities, independent evaluations of the half life and branching ratios have been
186 conducted combining experimental nuclear physics data with Ar-Ar ages from independently
187 dated minerals. Half lives calculated by Min et.al. (2000) and Renne et.al. (2010) using these
188 approaches are also given in Table 3.
189
190 There is also considerable variation in the mean beta energies reported in each library,
191 ranging from ~450 keV to ~520 keV, corresponding to 5-10% variation in dose rate
192 conversion factors. The major difference to the mean energy is the shape of the beta-
193 spectrum assumed. To determine the mean beta decay energy, it is necessary to know the
194 shape and end-point energy of the beta spectrum. The end-point energy is well defined from
195 the atomic mass difference between ^{40}K and ^{40}Ca, at 1311.07 ± 0.12 keV. The shape of the
196 beta spectrum is proportional to a factor pWq^2 for sharing momentum between the leptons,
197 the Fermi function *F(Z,W)* and a shape factor *C(W)*.

$$\frac{dN}{dW} \propto pWq^2\, F(Z,W)\, C(W)$$

where W is the total beta energy, Z is the atomic number of the daughter, p is the momentum of the beta particle and q the momentum of the neutrino. Theoretical shape factors for allowed or forbidden unique transitions are given by:

$$C(W) = (2L-1)! \sum_{k=1}^{L} \lambda_k \frac{p^{2(k-1)} q^{2(L-k)}}{(2k-1)!\,[2(L-k)+1]!}$$

where $L=\Delta J$, and $L=1$ for $\Delta J=0$. The parameter λ_k cannot be calculated in a straightforward manner, and typically an assumption that $\lambda_k=1$ is used.

The decay from ^{40}K (ground state 4^-) to ^{40}Ca (ground state 0^+) is a third unique forbidden (3U) transition. The commonly used LOGFT program for calculating the shape of the spectrum only calculates allowed and first and second unique forbidden (1U, 2U) transitions, and when presented with any other transition defaults to an allowed transition shape. Recalculations of the beta spectral shapes to evaluate the reliability of the $\lambda_k=1$ approximation (Mougeot 2015) have included the ^{40}K beta spectrum using an experimental shape factor from Leutz et.al. (1965). The program BetaShape (Mougeot 2015, 2016) has been used to generate spectra for different shape factors theoretically with the $\lambda_k=1$ assumption and for experimental shape factors reported in the literature. These spectra are plotted in Fig.3, with the data included in the supplementary material. The mean beta energies have been calculated for these, and given in Table 4 with corresponding mean energies from the LOGFT program for the allowed and first and second unique forbidden transitions. The mean energy for the Leutz et.al. (1965) shape factor is identical to that reported by Mougeot (2015). Recent high precision measurements of beta spectra have been conducted (Carles & Kossert 2007), proposing a shape factor of the form $C(W) = \lambda_1 p^6 + \lambda_2 q^6 + 7p^2q^2(p^2+q^2)$ for ^{40}K, with λ_1=1.8 and λ_2=1.23, to resolve discrepancies between cutoff energy yield and maximum point energy. However, the authors note that this form of

shape factor fails Cherenkov counting tests, and in correspondence stated that they consider the spectrum generated by BetaShape using the Leutz et.al. (1965) shape factor is “the best choice for K-40 at this moment” (Kossert pers. comm..)

Comparing the mean energy per decay in the different evaluations (Table 3) with the calculated mean energies for different shape factors (Table 4) it appears that the JEFF 3.11 and DDEP evaluators have used the LOGFT program, letting the program default to an allowed transition shape. The DDEP evaluators (Mougeot & Helmer 2009) state that the mean energy is given by the LOGFT program without further elaboration. The mean energy reported by the ENSDF evaluation is consistent with forcing the LOGFT program to use a 2U shape factor, which would be closer to the 3U value. And, the JEF2.2 evaluators have a value consistent with the Leutz et.al. (1965) shape factor, with a marginally larger endpoint energy. It is noted that Lederer & Shirley (1978) also give a mean energy for ^{40}K beta decay of 583 keV, and this value is explicitly stated in the calculations of dose rate conversion factors of Aitken (1983, 1985), Bell (1976), Nambi & Aitken (1986) and Sanderson (1987). Subsequent calculations use the lower mean energy in the ENSDF library, Adamiec & Aitken (1998) note that this leads to a 4% reduction in the ^{40}K beta conversion factor.

The beta spectrum is also required to calculate absorbed dose fractions. Mejdahl (1979) recognised that this is a third unique forbidden transition, and used a spectrum transformed from a corresponding allowed shape using the method of Wu & Moszkowski (1966). Nathan et.al (2003) used a Fermi model spectrum with spectral factors from Behrens & Szybisz (1976), with the spectrum given in the supplementary information of Guérin et.al. (2012) having a mean energy of 508 keV, consistent with the use of an allowed spectral shape despite statements that spectral factors had been used.

4. Discussion and Conclusions

The estimation of dose rate from radionuclide concentrations requires accurate nuclear data covering half lives, branching ratios, emission energies and intensities. The use of evaluated libraries provides a convenient means of accessing this data to calculate conversion ratios. The evolution of the evaluated library reported in *Nuclear Data Sheets* and *Table of Isotopes*, and more recently formalised in the Evaluated Nuclear Structure Data File (ENSDF), has resulted in a variety of dose rate conversion factors being determined. However, with two additional sets of evaluations; the NEA/OECD JEF2.2 and JEFF3.11 libraries tailored for nuclear reactor and nuclear medicine applications, and the Decay Data Evaluation Project (DDEP); an assessment of the variations in relevant nuclear data across current versions of these different libraries has been conducted with the intention of identifying if the different evaluation processes significantly bias the resulting evaluated data and to identify which radionuclides might carry significant variations, and thus be needing further measurements to refine the nuclear data.

In the uranium series, combining both ^{235}U and ^{238}U, the JEF2.2/JEFF3.11 gamma conversion factors are 0.7% higher than the corresponding ENSDF/DDEP values, and conversely the beta conversion parameters are 1.5% lower. It has been shown that these differences are mostly due to differences in the data for ^{214}Bi. These differences are due to the inclusion of a single high precision data set (Morel et.al. 2004) in the more recent ENSDF/DDEP evaluations. Although the absolute intensity of the 609 keV gamma ray from this is consistent with other measurements since the 1980s, within a 1-2 σ limit, the ENSDF/DDEP evaluations are heavily biased to this single data set. It would be of benefit if an independent high precision data set confirmed the measurements of Morel et.al. (2004). It is considered that the

ENSDF and DDEP evaluations, incorporating the Morel et.al. (2004) data, are the best available, with the differences between them insignificant. For the purpose of calculating dose conversion factors, the mean of these is used with an uncertainty assigned that encompasses the 1σ range of both values.

In the thorium series, the gamma conversion factors from the ENSDF/DDEP libraries are ~3.5% lower than for the JEF2.2/JEFF3.11 libraries. It has been shown that these differences are largely derived from differences in the ^{228}Ac nuclear data. Although this has not been examined in detail here, the DDEP evaluator (Pearce 2009) noted that the decay data for this radionuclide is incomplete with an ~7% discrepancy between beta and gamma intensity data, and recommended that further experimental gamma data be collected with particular emphasis on low energy gammas and coincidence measurements to confirm the level scheme. It is considered that the ENSDF/DDEP evaluations are the likely to underestimate total gamma and beta energies per decay by 2-4%, and for this work it has been assumed that the ENSDF/DDEP values should be used with an additional 3% added to them, with the uncertainty increased by 10%.

For ^{40}K and ^{87}Rb, there is considerable variation in both beta and gamma dose conversion factors between the four contemporary evaluated libraries and the literature values from different versions of the ENSDF library, with 3-12% variation in the beta conversion parameters and 1-4% variation for the gamma conversion parameters. These variations reflect differences in ^{40}K nuclear data in different evaluations; with 2-5% variation in half life values, upto 15% variation in mean beta energy, and small variations in branching ratios.

The ^{40}K half life is also critical to geochronology, and independent evaluations of nuclear data and Ar-Ar measurements of known age minerals by the geochronology community has produced half-life values consistent with the latest ENSDF and DDEP evaluations with similar precision of ~0.2%. The mean of the ENSDF & DDEP values for the half life has therefore been taken as the best value currently available, with uncertainties to encompass the 1σ range of both values. The dominant difference between evaluated libraries is the mean beta decay energy, which reflects the shape of the decay spectrum used. The LOGFT program most commonly used to calculate mean energies and branching ratios does not include the 3U transition needed to model the ^{40}K decays to ^{40}Ca and the ^{40}Ar ground state. Thus, approximations are made in the calculations of mean energy and branching ratio, the difference in mean energy reflects the difference between using a 2U or an allowed transition as an approximation to the 3U transition. The use of an alternative program, BetaShape, that does allow for 3U shape factors results in an increase in the calculated mean energy. At present, experimental shape factors for the ^{40}K decay are poorly measured, especially in the low energy (<100 keV) region, and additional precision measurements of the ^{40}K beta spectrum would be of considerable benefit in more accurately determining experimental shape factors. However, it would be surprising if future experimental data results in a mean energy significantly different from 585 ± 5 keV, with the best current measurement giving a mean energy of 583.98 ± 0.10 keV (Leutz et.al. 1965, Mougeot 2015) which includes an uncertainty twice that given by this shape factor.

Based on our assessment of what are currently the best nuclear data as reviewed here, dose rate conversion factors can be calculated (Table 5). In most cases, these are consistent with values currently regularly used (Adamiec & Aitken 1998, Guérin et.al. 2011, Liritzis et.al. 2013). The exception is the K+Rb beta parameter which is approximately 4% larger, in line

with earlier calculations using the 583 keV mean energy of Lederer & Shirley (1978), including the calculations of Aitken (1983) which had been widely used prior to adoption of the newer values. It should be noted that although these conversion factors are determined using our assessment of the best available data, there are still serious doubts regarding that data. As such, these factors are provisional subject to clarification of the inconsistencies in the nuclear data.

These conversion factors have been used to calculate dose rates for a standard mineral composition following the assumptions of Adamiec & Aitken (1998) for alpha efficiency, beta attenuation and cosmic contributions. These are given in Table 6 with values given by Adamiec & Aitken (1998) for comparison. In all instances, the total dose rates are slightly larger than those calculated by Adamiec & Aitken (1998), and generally in agreement with those of Nambi & Aitken (1986) except for ^{40}K (where the current work predicts higher dose rates) and Th gamma.

It is clear that the choice of dose rate conversion factors to be used is still to be fully resolved. The values suggested here may be used, but without resolution of significant doubts in the nuclear data it may be preferable to maintain continuity with prior work by not changing the values used with each new revision. Whatever values are used, it should be recognised that propagating uncertainties in the evaluated libraries would underestimate the true uncertainties. In this work, uncertainties in the parameters are in the range of 1-3%, previous studies (Aitken 1985, following Bell 1979) have noted that 5% is the maximum error likely to occur. In addition, the values used should be clearly stated when reporting dose rates.

Acknowledgements

The authors acknowledge with thanks the constructive discussions with Dr Ryan Ickert (SUERC) regarding ^{40}K half life evaluations used in Ar-Ar dating.

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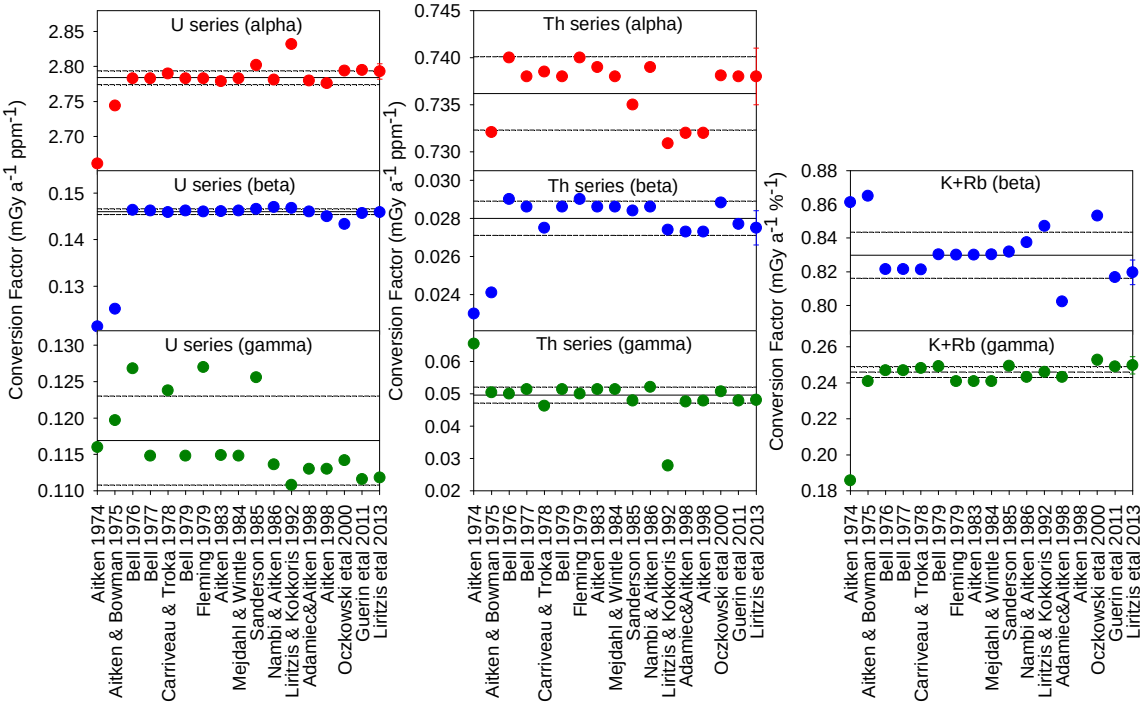

474 Figure 1: Dose rate conversion factors for the uranium series (^{235}U + ^{238}U), Th series (^{232}Th)

475 and ^{40}K taken from the literature. The control lines show the robust mean ± 1 standard

476 deviation.

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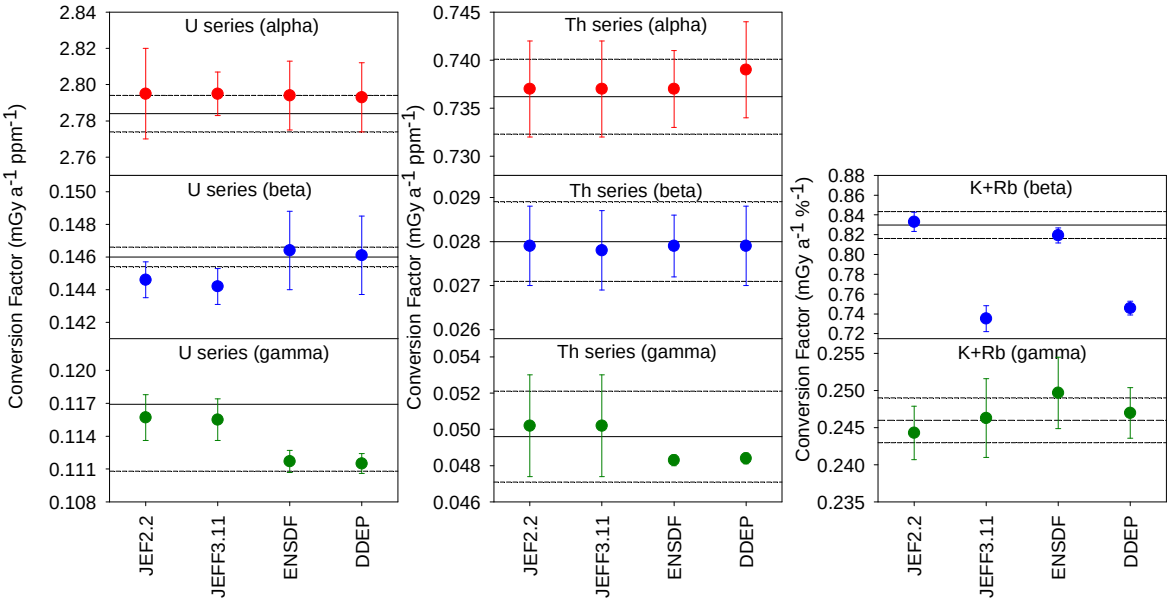

478 Figure 2: Dose rate conversion factors for the uranium series (^{235}U + ^{238}U), Th series (^{232}Th)
479 and ^{40}K calculated from four evaluations. The control lines show the robust mean ± 1
480 standard deviation from previous literature values (Fig. 1).

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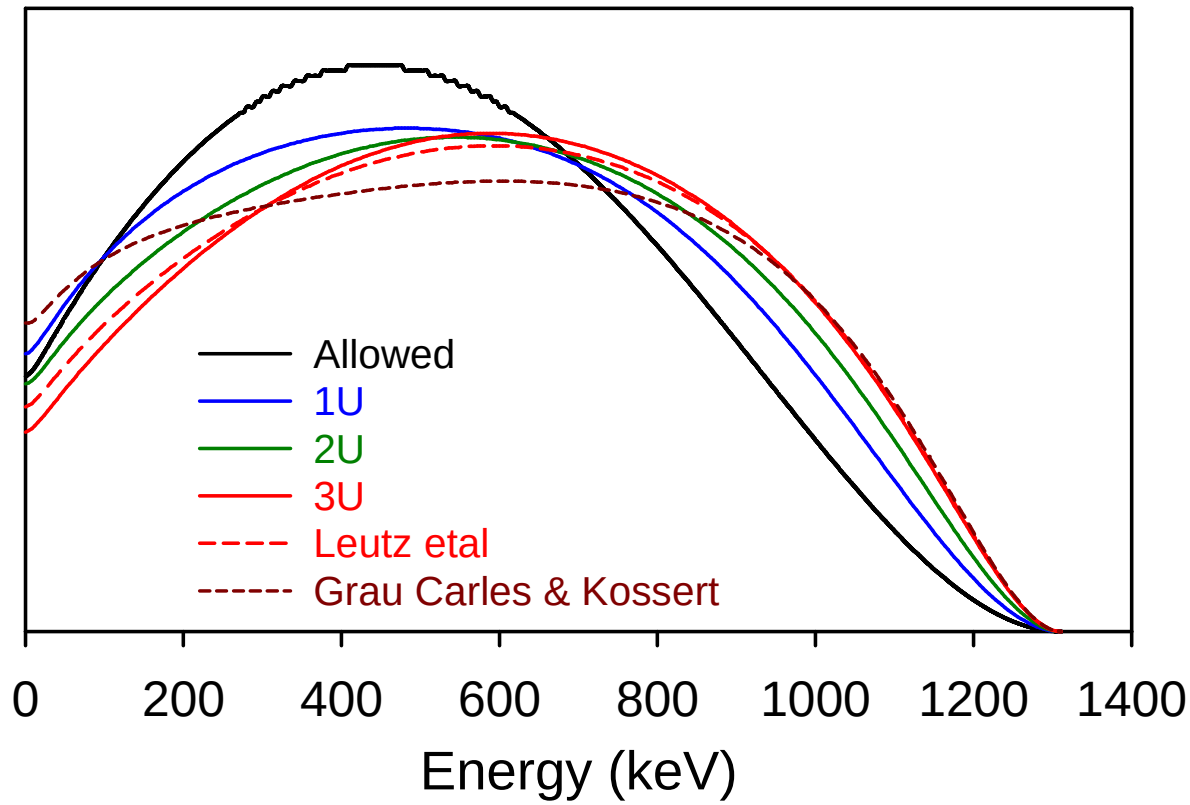

482 Figure 3: Beta spectra calculated by the BetaShape program (Mougeot 2015, 2016) using
483 theoretical shape factors, with the λ_k=1 assumption, for allowed and first, second and third
484 unique forbidden transitions, and for experimentally derived shape factors reported by Leutz
485 et.al. (1965) and Carles & Kossert (2007). All spectra are calculated using an endpoint energy
486 of 1311.07 keV.
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490 Table 1: Mean gamma and beta energies per decay of ^{214}Bi calculated from different

491 evaluated libraries

	Mean energy per decay (keV)	
	Gamma	Beta
JEF 2.2/JEFF 3.11	1536.9 ± 30.3	613.7 ± 15.5
ENSDF	1474.1 ± 1.6	640.0 ± 3.3
DDEP	1467.8 ± 1.9	645.8 ± 3.7

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494 Table 2: Mean gamma energies per decay of ^{228}Ac calculated from different evaluated

495 libraries

	Mean energy per decay (keV)
JEFF 3.11	955.6 ± 133.8
ENSDF	864 ± 10
DDEP	864 ± 10

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499 Table 3: ^{40}K half lives, beta- branching ratios and energies from different evaluations

	Half life ($x10^9$ a)	End point (keV)	Mean energy / beta decay (keV)	Branching %	Mean energy / 40K decay (keV)
JEF2.2	1.280 ± 0.010	1311.6 ± 0.5	584.9 ± 0.6	0.893 ± 0.001	521.48 ± 0.62
JEFF 3.11	1.265 ± 0.020	1311.04 ± 0.12	508.29 ± 0.05	89.15 ± 0.13	453.16 ± 0.66
ENSDF	1.248 ± 0.003	1311.07 ± 0.12	560.18 ± 0.05	89.14 ± 0.18	499.3 ± 1.0
DDEP	1.2504 ± 0.0030	1311.07 ± 0.12	508.32 ± 0.05	89.25 ± 0.17	453.68 ± 0.87
Min etal (2000)	1.269 ± 0.025				
Renne etal (2010)	1.2479 ± 0.0024				

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Table 4: Mean beta energies calculated for an endpoint energy of 1311.07 keV using the BetaShape program (Mougeot 2015, 2016) for theoretical shape factors, assuming λ_k=1, and experimentally measured shape factors. With mean energies from the LOGFT program for comparison.

	C(W)	Mean beta energy (keV)	
		BetaShape	LOGFT
Allowed	1	507.83 ± 0.05	508.31 ± 0.05
1U	$p^2 + q^2$	536.08 ± 0.05	534.04 ± 0.05
2U	$p^4 + q^4 + \frac{10}{3}p^2q^2$	563.01 ± 0.05	560.18 ± 0.05
3U	$p^6 + q^6 + 7p^2q^2(p^2 + q^2)$	587.89 ± 0.05	
Leutz et.al. 1965	$0.95p^6 + 1.05q^6 + 6.3p^2q^4 + 6.25q^2p^4$	583.98 ± 0.05	
Carles & Kossert 2007	$1.8p^6 + 1.23q^6 + 7p^2q^4 + 7q^2p^4$	569.26 ± 0.05	

509 Table 5: Dose rate conversion factors based on current best nuclear data. The data used are
510 from the DDEP library with the exception of ^{214}Bi (mean of ENSDF and DDEP), ^{228}Ac (the
511 ENSDF and DDEP values increased by 3%) and ^{40}K mean beta energy (from the Leutz et.al.
512 1965 shape factor), and ^{87}Rb, ^{230}Th, ^{228}Ra and ^{227}Th which are not currently included in the
513 DDEP library (ENSDF data used for these).

	^{238}U + ^{235}U mGy a^{-1} ppm^{-1}		^{232}Th mGy a^{-1} ppm^{-1}		^{40}K + ^{87}Rb mGy a^{-1} %$^{-1}$
	Total	Pre-Rn[1]	Total	Pre-Rn[1]	
Alpha	2.79 ± 0.02	1.27 ± 0.01	0.738 ± 0.004	0.309 ± 0.002	
Beta	0.142 ± 0.002	0.056 ± 0.001	0.028 ± 0.001	0.0096 ± 0.0007	0.854 ± 0.008
Gamma	0.112 ± 0.001	0.0037 ± 0.0001	0.0489 ± 0.0003	0.0188 ± 0.0002	0.248 ± 0.003

514 [1] The columns labelled 'Pre-Rn' give values for 100% escape of radon for ^{238}U and ^{232}Th, but
515 include the full ^{235}U decay series due to the short half life of ^{219}Rn, following the approach of
516 Adamiec & Aitken 1998.
517
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519 Table 6: Dose rates (mGy a^{-1}) for a standard concentration from Nambi & Aitken, 1986
520 (N&A 86), Adamiec & Aitken 1998 (A&A 98) and the current work, assuming zero moisture
521 content.

		1% K	50 ppm Rb	3 ppm Th	1 ppm U	Total
Effective alpha[1]	N&A 86			0.190	0.222	0.413
	A&A 98			0.183	0.218	0.401
	This work			0.190	0.223	0.413
Beta	N&A 86	0.814	0.023	0.086	0.147	1.071
	A&A 98	0.782	0.019	0.082	0.146	1.029
	This work	0.835	0.019	0.084	0.142	1.080
Gamma[2]	N&A 86	0.243		0.156	0.114	0.693
	A&A 98	0.243		0.143	0.113	0.679
	This work	0.247		0.147	0.112	0.686
Fine-grain total	N&A 86	1.058	0.023	0.433	0.489	2.18
	A&A 98	1.025	0.019	0.408	0.477	2.11
	This work	1.082	0.019	0.421	0.477	2.18
Coarse grain total[3]	N&A 86	0.976	0.018	0.234	0.246	1.65
	A&A 98	0.947	0.014	0.217	0.244	1.60
	This work	0.999	0.014	0.223	0.240	1.66

522 [1] Effective alpha dose rates are derived using k=0.1 and k_{eff} = 0.86 (Th) and 0.80 (U),
523 following Adamiec & Aitken (1998).

524 [2] Total gamma includes 0.180 mGy a^{-1} as a cosmic component, following Adamiec & Aitken
525 (1998).

526 [3] Beta attenuation factors for coarse grains taken as 0.90, except for Rb which is taken as
527 0.75, following Adamiec & Aitken (1998).

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