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Heavy Element and Actinide Decay Data: UKHEDD2.6

Report to Nexia Solutions Ltd

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Executive Summary

The latest version of the UK Heavy Element and Actinide Decay Data Library (UKHEDD2.6) is described in this report, as defined in February 2008.

The decay data of various radionuclides have been evaluated on the basis of a series of well-defined requirements and specifications of the UK nuclear power, fuel reprocessing and waste management programmes. UKHEDD2.6 contains recommended decay data for the actinides that constitute reactor fuels and are formed through an extensive series of neutron reactions prior to and including their natural radioactive decay. Recommended data include half-lives, branching fractions, alpha, beta and gamma-ray energies and emission probabilities, total decay energies, mean alpha, beta and gamma energies, internal conversion coefficients, and all associated uncertainties. Computer-based files have been generated in ENDF-6 format, including lists of the references used to produce the proposed decay schemes and comments that identify any observed inadequacies.

Decay scheme data for UKHEDD were first evaluated and assembled as an ENDF-formatted database by A L Nichols and M F James between 1977 and 1981; all subsequent re-evaluations have been carried out by A L Nichols[1].

The previous version of the library, UKHEDD2.5, was released in February 2007. This library had been assembled over a number of years and the structure of many of the older files no longer conformed to modern standards, causing difficulties in the assimilation of data from UKHEDD into the JEFF-3 decay data file. Thus, all data sets within UKHEDD2.6 have been updated to bring them to the required standard and to facilitate the assimilation of the data into JEFF-3 and future libraries. No new evaluations have been undertaken for this release, with the changes being confined to the basic structure of the files.

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1 Introduction

The UK Heavy Element and Actinide Decay Data Library was first released by A L Nichols and M F James in 1981 as UKHEDD1 (1). Subsequently, improvements in the available decay data through various laboratory measurements led to a comprehensive evaluation of the decay data for all 125 radionuclides, and the release of UKHEDD2 in 1991 (2). Since this release, a significant number of radionuclides have continued to be re-evaluated by A L Nichols with the aim of producing and maintaining recommended libraries of relevant nuclear data. This has led to a gradual improvement of the UKHEDD library funded largely by BNFL plc.

The previous version of the library was released in February 2007 as UKHEDD2.5 (3). This library had been assembled over a number of years and the structure of many of the older files no longer conformed to modern standards, causing difficulties in the assimilation of data from UKHEDD into the JEFF-3.1.1 decay data file (4). Thus, all data sets have been re-visited and updated for UKHEDD2.6 to bring them to the required standard and to facilitate the assimilation of the data into JEFF-3 and future libraries. No new evaluations have been undertaken for this release, with any changes confined to the structure of the files.

The current library consists of recommended decay data files for 125 radionuclides, 50 of which have been re-evaluated since the release of UKHEDD2. UKHEDD libraries are made available to the international community via the NEA Data Bank, and any new evaluations are submitted for possible inclusion in the JEFF-3 decay data library.

The evaluation procedure and contents of UKHEDD2.6 are summarised in the following sections.

2 Decay Data

UKHEDD2.6 contains recommended data for the following parameters (see also Section 4):

(i) half-lives,

(ii) total decay energies (Q-values),

(iii) branching fractions,

(iv) alpha-particle energies and emission probabilities,

(v) beta-particle energies, emission probabilities and transition types,

(vi) gamma-ray energies, emission probabilities and internal-conversion coefficients,

(vii) neutron energies and emission probabilities,

(viii) spontaneous fission data including prompt gamma-ray spectra.

The spin and parity of the decaying nuclide have been defined, and uncertainties are assigned to all of the evaluated data. Other data in UKHEDD2.6 (mean energies, discrete electrons and mean X rays) were derived from the above data by using the processing code COGEND (5). The component contributions to the average energies (light particle, electromagnetic and heavy particle) are derived from the evaluated input data by COGEND. This code also contains data libraries of fluorescence yields, Auger-electron energies, mean x-ray energies and electron-wave-function ratios from which capture ratios can be calculated.

The library has been generated in ENDF-6 format (6). There is a general information section for each nuclide which contains:

(i) name of the evaluator and date of the evaluation (month and year),

(ii) list of references used to construct the recommended data set,

(iii) detailed comments associated with the evaluation,

(iv) consistency check of the evaluated data.

The recommended decay data are contained within the main data section. Every effort has been made to produce consistent and comprehensive data sets. Conversion electrons are particularly important in the decay of actinides and heavy elements, and they have been calculated from the evaluated gamma-ray data and their internal conversion coefficients. When necessary, theoretical internal conversion coefficients have been used in conjunction with the evaluated gamma-ray data. X-ray data were derived from the energy and emission probability data held within COGEND (7, 8).

All of the energy data are in eV, and the absolute emission probabilities are expressed as fractions of the decay (calculated from the spectral normalisation factor and relative emission probabilities). The data in UKHEDD2.6 are listed as described in Reference 6, and summaries of the contents of the updated library are given in Tables 1 and 2.

The consistency of the recommended data has been determined by calculating the percentage deviation between the effective Q-value and the calculated Q-value:

$$\text{effective Q-value} = \sum_{i=1}^{\text{all BF}} Q_i.BF_i \qquad (1)$$

where Q_i and BF_i are the Q-value and branching faction of the i^{th} decay mode (i.e. weighted sum of the evaluated Q-values of the radionuclide),

$$\text{calculated Q-value} = \sum_{i}^{\text{all } \alpha} E_{\alpha_i} P_{\alpha_i} + \sum_{j}^{\text{all } \beta} E_{\beta_j} P_{\beta_j} + \sum_{k}^{\text{all } \gamma} E_{\gamma_k} P_{\gamma_k} + \sum_{l}^{\text{all x-rays}} E_{x_l} P_{x_l} + \text{etc.} \qquad (2)$$

where $E_{\alpha_i}, E_{\beta_j}, E_{\gamma_k}, E_{x_l}$, etc., and $P_{\alpha_i}, P_{\beta_j}, P_{\gamma_k}, P_{x_l}$, etc.

are the energies and emission probabilities of the i^{th} alpha particle, j^{th} beta particle, k^{th} gamma ray, l^{th} x ray, etc. of the individual decay process.

The percentage deviations of the data in the UKHEDD2.6 library are given in Table 1. Percentage deviations above 5% would be regarded as high and imply a poorly defined decay scheme; a value of less than 5% indicates the construction of a reasonably consistent decay scheme.

3 Evaluation Procedure

3.1 Overview

An initial decay scheme was constructed for each radionuclide from a suitable combination of the various data sources. The evaluation procedure was as follows:

(i) assess the status of the existing data,

(ii) identify data discrepancies,

(iii) evaluate and recommend decay data.

The emission probabilities have been expressed as the absolute probability of the transition (α, β, conversion electron, X-ray or γ ray) per decay. All available measurements were generally taken into account during an evaluation, including experimental data from laboratory reports and written private communications. Comprehensive statements of the precise evaluation procedure were prepared after each assessment, as well as details of any changes made to the reported data. Under specific circumstances, the evaluations involved the determination of a weighted mean for each parameter. No individual measurement was allowed to contribute more than 50% to the sum of weights when more than one value of the same parameter was reported, and the uncertainty of the datum was increased if necessary. If the set of accepted experimental data proved to be inconsistent, one of several possibilities was adopted:

(i) recommend the unweighted mean,

(ii) reject some measured values on the basis of objective or subjective judgements (e.g. inappropriate calibration procedure or ill-defined measurement techniques employed by the metrologist),

(iii) change the weights.

An appropriate method of changing weights was preferred rather than outright rejection of data. Any serious problems encountered during an evaluation are described in the Comments Section associated with each nuclide in the library. If the resulting decay scheme has any outstanding problems, a statement was made to the effect that better measurements are required.

3.2 Procedures and Consistency Checks

The following procedures and consistency checks form the basis of the evaluation strategy used to update and improve the UKHEDD library.

(i) Every effort was made to ensure that there was a reasonable emission-probability balance between the population and de-population of all excited levels in the decay scheme.

(ii) All decay modes of each radioactive nuclide were completely specified in terms of both the branching ratios and the Q-values. The Q-value, defined as the energy difference between the initial and final states, takes account of the energies of any metastable states which are involved in the decay.

(iii) The sum of all α, β^-, β^+/electron-capture and isomeric gamma-emission probabilities were consistent with the corresponding branching fractions.

(iv) Gamma-ray emission probabilities must be the photon probabilities per disintegration and were listed as percentages in the data files. This means that relative photon probabilities were normalised in a consistent manner.

(v) Internal-conversion coefficients for gamma-ray transitions were consistent with both the photon and total transition probabilities,
i.e. (photon + conversion electron) emission probabilities = total transition probability.

(vi) When the internal conversion of a gamma-ray transition was significant, theoretical internal-conversion coefficients were adopted if experimental data were unavailable. This ensured that the transition energy was appropriately shared between the electromagnetic and electron components.

(vii) The nature of the beta transition was taken into account in the calculation of mean beta energies from the evaluated end points. This information was inferred from the spin and parity assignments proposed for the levels involved.

(viii) Energies and emission probabilities of conversion electrons, Auger electrons, X rays and annihilation radiation were derived in a consistent manner.

(ix) Uncertainties were estimated for all of the parameters incorporated into UKHEDD2.6.

(x) Each evaluation was fully documented. The evaluated ENDF-6 files include a descriptive section that includes comments on inconsistencies and any assumptions made by the evaluator to deal with such problems.

3.3 Production Procedure

(i) The evaluation is undertaken and the initial input data are prepared by the evaluator.

(ii) The evaluation is converted into a form suitable for input to COGEND.

(iii) The COGEND input data are checked against the original evaluation.

(iv) The COGEND code is run and the input file and ENDF-6 output file are sent to the evaluator for checking.

(v) Any corrections and improvements are defined by the evaluator, and COGEND is rerun until he/she is satisfied with the results.

COGEND generates an ENDF-6 format file. The computer codes CHECKR (9) and FIZCON (10) are applied to the file. Any diagnostic reports from these codes are reported to the evaluator who directs any further changes necessary.

4 Heavy Element and Actinide Decay Data Library, UKHEDD2.6

4.1 Changes Since the Last Release

The changes made for this release of the library have been applied to ensure that the structure of the evaluated files conforms to modern standards and to facilitate the assimilation of the data into JEFF-3 and future libraries. However, these changes have not affected the evaluated decay data which are unchanged from the previous release.

The main tool used to re-structure the files was the ENDF-6 utility code STANEF7.02 (9). Using the default options, this code performs the following actions:

sets the chemical symbol to mixed case, e.g. Pu,

reconstructs the file directory to ensure consistency with the evaluated data, converts numeric fields to the standard ENDF-6 form.

These changes were applied to all 125 nuclides in UKHEDD2.6. Furthermore, a number of other changes were applied to selected nuclides, as outlined below.

The second field of the third record of the General Information Section of an ENDF-6 format file contains the parameter EMAX, the maximum energy for the evaluation (6). This parameter has no meaning for decay data files and should be set to zero. However, EMAX had been set to 20 MeV for 23 nuclides in UKHEDD2.5, and therefore EMAX values for these nuclides were re-set to zero.

The ENDF-6 material (MAT) number used for many of the nuclides was no longer consistent with the value expected by the latest version of the ENDF-6 format checking code CHECKR7.02 (9). MAT numbers for these nuclides were altered to the values expected by CHECKR7.02, thus ensuring a consistent set of MAT numbers has been adopted for all nuclides.

When processing nuclides that undergo spontaneous fission, COGEND forms the product of the average number of neutrons ($\bar{\nu}$) and the spontaneous fission branching fraction, and assigns this value to the continuum spectrum normalisation factor associated with the spontaneous fission neutron spectrum. More recent versions of COGEND have also written the spontaneous fission $\bar{\nu}$ explicitly to MF1, MT452, and this convention is used in JEFF-3 decay files. The $\bar{\nu}$ values used in UKHEDD2.6 were evaluated by James (1), who approximated the total number of neutrons per fission to be the number of prompt neutrons per fission because the number of delayed neutrons is relatively small and often unknown. This systematic difference is believed to be within the uncertainty of the prompt contribution. The spectrum of emitted neutrons is included in the decay data (MF8). Since the spontaneous fission $\bar{\nu}$ was not included in MF1/MT452 of 16 of the older evaluations, the files were updated to include these data. The nuclides affected were Th-230, Th-232, Pa-231, U-232, U-234, Pu-242, Pu-244, Am-243, Cm-246, Cm-248, Cm-250, Bk-249, Cf-249, Cf-250, Cf-252 and Es-253.

All 125 files comprising UKHEDD2.6 were checked using CHECKR7.02 and FIZCON (10). There were no diagnostic reports from CHECKR7.02. FIZCON produced diagnostic messages for a number of nuclides, as described below.

normalization check integral = 9.97115E-01

This message was present for 16 older evaluations of nuclides that undergo spontaneous fission, as listed above. The spontaneous fission neutron spectra for these nuclides were taken from the work of James (1), and the diagnostic message relates to a known problem with the James spectra - they do not integrate to unity, although this anomaly is small compared with the overall uncertainties in the formula used to derive the spectra. Thus, no action was taken to correct the discrepancy for these nuclides. However, for spontaneous fission nuclides that have been re-evaluated sine 1999, the discrepancies have been removed by simply re-normalising the spectra.

elis not in range 0.00000E+00 to 0.00000E+00

This message is present for all metastable nuclides. The parameter ELIS is the excitation energy (6) and is non-zero for metastable nuclides. FIZCON checks that this parameter is between zero and EMAX, the upper energy of the evaluation. EMAX is zero for decay data files, and therefore the message does not apply to decay data files and can be ignored.

ft value too small

This message occurred for Bi-214, Ra-288, Th-233 and U-239. FIZCON checks that the ft value for beta transitions is within certain limits dependent on the transition type. Although beta transitions that fail this test had been individually assessed at the time of evaluation, the evaluator believed that this condition could not be averted.

In addition to the above, various messages relating to energy sum-up discrepancies were present for the incomplete evaluations of Bi-215, Po-209, Th-235 and Pa-235. Further details of these evaluations are given in Section 4.2 below.

4.2 Contents of the Library

The UKHEDD2.6 evaluated decay data library contains comprehensive decay data for 125 radionuclides. This library has been assembled in the internationally-accepted standard ENDF-6 format adopted for nuclear applications, as described in Reference 6.

A General Information/Descriptive Data Section is defined for each nuclide (MF=1, MT=451) that contains the following information:

(i) radionuclide, date of evaluation, name of evaluator, date of distribution (month, year) and most recent date of issue (year, month and day);

(ii) library name (UKHEDD2.6), file identifier (material number), data type (radioactive decay data) and format type (ENDF-6);

(iii) list of references used to determine the recommended data set;

(iv) detailed comments concerning the evaluation;

(v) specific decay data not contained in the main decay data section, including beta-particle transition parameters;

(vi) consistency check of the recommended data set.

The recommended decay data are contained within the primary data section (MF=8, MT=457). These data are:

(i) spin and parity of the decaying radionuclide;

(ii) half-life;

(iii) average energy per disintegration for three general radiation types (light particles, electromagnetic radiations and heavy particles) followed (for evaluations since September 2002) by the individual components of these types;

(iv) decay modes, Q-values and branching fractions;

(v) radiation decay data, including gamma-ray, beta-particle, electron-capture, alpha-particle, neutron, discrete electron and x-ray transitions;

(vi) spontaneous fission decay data.

The various decay parameters of the majority of radionuclides in UKHEDD2.6 have been reasonably well defined in the published literature, and were evaluated with good precision and confidence to produce consistent decay schemes. However, the relevant data for seven of the nuclides proved insufficient (at the time of evaluation) to recommend complete decay schemes. The details given in the comments section of the ENDF-6 files for these nuclides are reproduced below - references associated with these particular comments are not defined in the reference list of this report, but can be found in the original database.

Bi-215
No decay data have been published for this nuclide. The half-life has been measured by following the alpha decay of daughter Po-215, but the activity was far below that expected. Even this measurement is highly suspect, Nurmia *et al.* reporting that the activity could not be chemically identified as bismuth.

The spin and parity (–9/2) have been assigned by comparing with the equivalent Bi- and Po-211 and 213 ground level assignments.

Detailed beta and gamma studies are required.

Po-209
Only the 260.5-, 262.8- and 896.4-keV gamma transitions have been observed in the decay of Po-209. The other low intensity gamma transitions have been derived from the equivalent decay data of Bi-205 and the low intensity alpha data of Hagee *et al.* - these data are extremely tentative. Alpha decay to the ground state and first excited state of 2.33 keV totals 99.3% - the relative populations of these two states have not been measured, but estimates of 20% to the ground level and 80% to the 2.33-keV level have been made.

The total internal conversion coefficient for the 2.33-keV gamma transition consists of contributions from the n, p and o electron shells. These data have been added to the file without accounting fully for the conversion electron contribution.

Th-235
No decay data have been published. The U-238 (n,alpha) cross-section studies of Trautmann *et al.* have resulted in the half-life measurement and the comment that five gamma transitions were observed: 416.2, 659.4, 727.2, 747.0 and 931.8 keV. No intensities have been determined for these gamma emissions, making it impossible to postulate even a partial decay scheme. The spin and parity (+5/2) have been assigned by comparing with the equivalent Th- and Pa-231 and 233 ground level assignments; the spin could as easily be 1/2.

Detailed beta and gamma decay studies are required.

Pa-235
Decay data are very scanty. It has been assumed that the daughter decay is U-235m and the major beta emission is first forbidden non-unique.

The gamma data of Trautmann *et al.* (1970) have been adopted and minor energy adjustments have been made, guided by the equivalent accurate decay data of Pu-239. The calculated gamma normalisation factor is highly suspect and the relative gamma intensity data have been derived from the Pa-235 gamma spectrum figure of Trautmann *et al.* Compared with the equivalent Pu-239 gamma data, a number of transitions have not been observed: no attempt has been made to incorporate these transitions into this evaluation. Only the single beta emission has been reported.

Further beta and gamma decay studies are required.

Np-240
The decay scheme is poorly defined. The partial decay scheme has been developed by balancing the gamma transitions from the 100% beta populated 1308.6-keV level of Pu-240. A single beta transition has been assumed.

Detailed beta and gamma data measurements may improve the decay scheme.

Pu-245
There are considerable inconsistencies in the decay data. It is unfortunate that a detailed study by Wapstra *et al.* has only partially been published. The ORNL report only reports gamma emissions with energies greater than 800 keV. Greater emphasis has been placed on the data of Daniels *et al*. A number of low energy gamma transitions are required to depopulate seven Am-245 daughter levels populated in the decay: no attempt has been made to list these transitions. Twelve gammas cannot be placed in the partial decay scheme: 514.6, 642, 691, 702, 743.7, 822, 879.6, 925.4, 945.2, 975, 1007 and 1040.2 keV.

The beta intensities derived by Ellis from the gamma data and populating levels above 887 keV have been adopted. Intensities populating lower levels have been derived by the evaluator when possible. For levels less than 191 keV, the combined beta decay has been arbitrarily shared between seven levels. There is a significant need for beta decay and conversion electron measurements to aid in resolving the decay properties of nuclear levels below 191 keV.

Am-246
There is considerable doubt as to the identity of the ground and metastable states of Am-246. The data associated with a half-life of 39 m have been assigned to the ground state: the Q-value has been set 5 keV below the Q-value for the metastable state. Another problem involves the parity assignment (+) derived from the decay data of Pu-246: disagrees with the assignment proposed by Schmorak.

The detailed charged particle studies of Orth *et al.* and Fields *et al.* give strong evidence for the production of this isomer via the Pu-244(He,d)Am-246 reaction. However there are a number of inconsistencies: some unobserved gamma transitions have been introduced (50, 78, 148 and 685 keV), but a complete decay scheme has not been produced.

Detailed beta, gamma and conversion electron data may clarify the decay scheme and produce an accurate Q-value.

5 Conclusions

Since the official release of UKHEDD2, the UK Heavy Element and Actinide Decay Data Library has been improved over a number of years by the re-evaluation of some 50 radionuclides to take account of new measurements of key parameters.

All of the evaluated decay data have been assembled with other files from previous versions of UKHEDD to create the UKHEDD2.6 library in ENDF-6 format (125 radionuclides, as listed in Table 1). Rigorous consistency checks have been made to confirm the validity and completeness of the data before releasing the updated library. The structure of all 125 evaluated files has been updated to ensure the files are consistent with modern standards and can be assimilated into JEFF-3 and future libraries. Comprehensive details of each evaluation can be found within the Comments Section of individual ENDF-6 files.

UKHEDD2.6 is available via the NEA Data Bank. All the decay data comprising UKHEDD2.6 have been submitted for possible inclusion in the JEFF-3 Decay Data Library.

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Table 1. Decay Data Summary

Nuclide	Evaluation Date	$T_{1/2}$	Decay Modes	Q % Deviation
80-Hg-206	AUG04	8.310m	β-	0.0610
81-Tl-206	MAR04	4.202m	β-	-0.0050
81-Tl-206m	APR91	3.760m	IT	0.0090
81-Tl-207	APR91	4.770m	β-	-0.0009
81-Tl-207m	APR91	1.330s	IT	-0.0084
81-Tl-208	SEP02	3.060m	β-	0.0088
81-Tl-209	APR91	2.2m	β-	0.0429
81-Tl-210	JUN04	1.3m	β-(0.99993), β-n(0.00007)	0.0191
82-Pb-205	DEC93	1.53003E+07y	EC	1.9227
82-Pb-209	APR91	3.253h	β-	0.0000
82-Pb-210	FEB04	22.160y	β-(1.0), α(1.90E-08)	-0.4568
82-Pb-211	APR91	36.1m	β-	0.0003
82-Pb-212	SEP02	10.640h	β-	0.0931
82-Pb-214	APR04	26.8m	β-	0.0263
83-Bi-210	FEB04	5.012d	β-(0.9999990), α(1.32E-06)	0.0000
83-Bi-210m	APR91	3.00006E+06y	α	-0.1748
83-Bi-211	APR91	2.170m	β-(0.00273), α(0.99727)	0.0025
83-Bi-212	SEP02	1.009h	β-(0.64056), β-α(0.00014), α(0.35930)	-0.0021
83-Bi-212m	AUG01	25.0m	β-(0.032), β-α(0.300), α(0.668)	-0.0437
83-Bi-212n	FEB05	9.0m	β-	0.0000
83-Bi-213	APR91	45.590m	β-(0.9784), α(0.0216)	0.0758
83-Bi-214	APR91	19.9m	β-(0.99979), α(0.00021)	0.0675
83-Bi-215	APR91	7.4m	β-	Incomplete
84-Po-209	APR91	102.002y	EC(0.0026), α(0.9974)	Incomplete
84-Po-210	FEB04	138.388d	α	-0.0014
84-Po-211	APR91	0.516s	α	-0.0006
84-Po-211m	APR91	25.5s	α	0.0784
84-Po-212	SEP02	3.0E-07s	α	-0.0013
84-Po-212m	APR02	45.1s	α	-0.0013
84-Po-213	APR91	4.2E-06s	α	-0.0049
84-Po-214	FEB04	1.637E-04s	α	-0.0013
84-Po-215	APR91	1.780E-03s	β-(4.0E-06), α(1.00)	0.0037
84-Po-216	SEP02	0.150s	α	-0.0009
84-Po-218	JAN04	3.098m	β-(0.00019), α(0.99981)	-0.0014
85-At-215	APR91	1.0E-04s	α	-0.0031
85-At-217	APR91	0.032s	β-(0.00012), α(0.99988)	-0.0083
85-At-218	JAN04	1.5s	β-(0.001), α(0.999)	-0.0012
85-At-219	APR91	54.0s	β-(0.030), α(0.970)	0.0043
86-Rn-217	APR91	5.4E-04s	α	-0.0053
86-Rn-218	JAN04	0.035s	α	-0.0006
86-Rn-219	APR91	3.960s	α	-0.0078
86-Rn-220	SEP02	55.8s	α	-0.0011
86-Rn-222	JAN04	3.823d	α	-0.0020
87-Fr-221	APR91	4.9m	α	-0.8061
87-Fr-223	APR91	21.8m	β-(0.99994), α(6.0E-05)	0.5535
88-Ra-223	APR91	11.430d	α	-0.1938

Nuclide	Evaluation Date	$T_{1/2}$	Decay Modes	Q % Deviation
88-Ra-224	SEP02	3.640d	α	0.0010
88-Ra-225	APR91	14.8d	β-	-0.0137
88-Ra-226	JAN04	1.60496E+03y	α	0.0013
88-Ra-228	APR91	5.750y	β-	0.3213
89-Ac-225	APR91	10.0d	α	0.3742
89-Ac-227	APR91	21.773y	β-(0.9862), α(0.0138)	0.2773
89-Ac-228	MAR95	6.150h	β-	-0.7282
90-Th-227	APR91	18.718d	α	-0.4859
90-Th-228	SEP02	1.913y	α	-0.0175
90-Th-229	APR91	7.34016E+03y	α	0.2975
90-Th-230	FEB03	7.54015E+04y	α(1.0), SF(2.5E-13)	0.1990
90-Th-231	MAR95	1.063d	β-	-0.7156
90-Th-232	APR91	1.40503E+10y	α(1.0), SF(1.4E-11)	-0.2622
90-Th-233	APR91	22.3m	β-	0.2179
90-Th-234	FEB96	24.090d	β-	0.1140
90-Th-235	APR91	6.9m	β-	Incomplete
91-Pa-231	FEB86	3.27608E+04y	α(1.0), SF(3.0E-12)	-0.0803
91-Pa-232	JAN02	1.310d	β-(0.99997), EC(3.0E-05)	-0.3363
91-Pa-233	APR91	27.0d	β-	-0.0793
91-Pa-234	APR93	6.780h	β-	-0.7946
91-Pa-234m	APR93	1.170m	β-(0.9985), IT(0.0015)	0.0348
91-Pa-235	APR91	24.2m	β-	Incomplete
92-U -232	MAY89	69.801y	α(1.0), SF(9.0E-13)	-0.0360
92-U -233	APR91	1.59253E+05y	α	-0.0825
92-U -234	JAN86	2.45705E+05y	α(1.0), SF(1.7E-11)	0.0067
92-U -235	DEC99	7.03814E+08y	α(1.0), SF(7.2E-11)	-0.0040
92-U -235m	AUG01	26.0m	IT	0.0000
92-U -236	DEC99	2.375E+07y	α(1.0), SF(9.0E-10)	-0.2605
92-U -237	APR91	6.750d	β-	0.1157
92-U -238	FEB07	4.46808E+09y	α(0.999999454), SF(5.46E-07)	0.0003
92-U -239	JAN91	23.470m	β-	-0.0099
92-U -240	APR91	14.1h	β-	-0.0670
93-Np-236	JAN02	1.52003E+05y	β-(0.1180), EC(0.8804), α(0.0016)	0.0884
93-Np-236m	FEB90	22.5h	β-(0.5), EC(0.5)	0.0723
93-Np-237	OCT88	2.14005E+06y	α	-0.1777
93-Np-238	MAY91	2.117d	β-	-0.0900
93-Np-239	MAY91	2.355d	β-	-0.1364
93-Np-240	MAY91	1.083h	β-	Incomplete
93-Np-240m	JAN02	7.4m	β-(0.9989), IT(0.0011)	-0.4742
93-Np-241	OCT89	13.9m	β-	-0.1891
94-Pu-236	MAR01	2.858y	α(1.0), SF(8.2E-10)	-0.0047
94-Pu-237	MAY91	45.3d	EC(0.9999580), α(4.2E-05)	1.2389
94-Pu-238	OCT04	87.7y	α(1.0), SF(1.86E-09)	0.0130
94-Pu-239	MAY01	2.41135E+04y	α(gd) (0.0006), α(m) (0.9994), SF(3.1E-12)	-0.0376
94-Pu-240	OCT04	6.563E+03y	α(1.0), SF(5.7E-08)	0.0077
94-Pu-241	JUL01	14.330y	β-(0.9999750), α(2.46E-05)	-0.0012
94-Pu-242	MAY91	3.73509E+05y	α(1.0), SF(5.5E-06)	0.0024
94-Pu-243	MAY91	4.956h	β-	0.0346
94-Pu-244	MAY91	8.00018E+07y	α(0.99875), SF(0.00125)	0.0048
94-Pu-245	MAY91	10.5h	β-	Incomplete

Nuclide	Evaluation Date	$T_{1/2}$	Decay Modes	Q % Deviation
94-Pu-246	MAY91	10.850d	β-	0.4786
95-Am-240	MAY91	2.117d	EC(1.0), α(1.9E-06)	0.0825
95-Am-241	FEB01	432.808y	α(1.0), SF(4.3E-12)	0.2443
95-Am-242	JAN00	16.040h	β-(0.832), EC(0.168)	0.0329
95-Am-242m	JAN00	141.003y	IT(0.99537), α(0.00463), SF(1.6E-10)	-0.5520
95-Am-243	FEB03	7.36498E+03y	α(1.0), SF(3.7E-11)	-0.0218
95-Am-244	MAY91	10.1h	β-	0.0002
95-Am-244m	MAY91	26.0m	β-(0.99959), EC(0.00041)	-0.0363
95-Am-245	MAY91	2.050h	β-	0.0470
95-Am-246	MAY91	39.0m	β-	Incomplete
95-Am-246m	MAY91	25.0m	β-	-0.4708
96-Cm-241	MAY91	32.8d	EC(0.990), α(0.010)	-0.5680
96-Cm-242	FEB01	162.931d	α(1.0), SF(6.1E-08)	-0.0394
96-Cm-243	MAY91	30.001y	EC(0.0024), α(0.9976)	-0.9741
96-Cm-244	OCT99	18.0y	α(0.9999990), SF(1.38E-06)	-0.0319
96-Cm-245	OCT89	8.50019E+03y	α	-0.0024
96-Cm-246	MAY91	4.73009E+03y	α(0.9997390), SF(0.0002614)	-0.0174
96-Cm-247	MAY91	1.60004E+07y	α	-0.0068
96-Cm-248	MAY91	3.40008E+05y	α(0.9174), SF(0.0826)	0.0057
96-Cm-249	MAY91	1.069h	β-	0.0430
96-Cm-250	MAY91	8.00018E+03y	α(0.3), SF(0.7)	-0.0005
97-Bk-249	JAN02	320.0d	β-(0.9999860), α(1.45E-05), SF(4.69E-10)	-0.4985
97-Bk-250	MAY91	3.217h	β-	-0.0287
98-Cf-249	MAY91	351.007y	α(1.0), SF(5.2E-09)	0.1430
98-Cf-250	MAY91	13.080y	α(0.99923), SF(0.00077)	-0.0045
98-Cf-251	MAY91	898.018y	α	-0.1201
98-Cf-252	MAY91	2.645y	α(0.96908), SF(0.03092)	-0.0710
98-Cf-253	MAY91	17.810d	β-(0.9969), α(0.0031)	-0.9361
99-Es-253	MAY91	20.470d	α(1.0), SF(8.7E-08)	0.0053

Incomplete files are described in Section 4.2 of the main text.

Table 2. Summary of Spectral Data

Continuum spectra are indicated by the letter ‘c’ following the number of discrete spectral lines. Thus, ‘15c’ indicates that there are 15 discrete lines followed by a continuum spectrum, and ‘0c’ indicates that only a continuum spectrum is present.

Nuclide	$T_{1/2}$ (s)	Mean Decay Energies (keV)			Number of Spectral Lines								
		Light Particle	Electro-magnetic	Heavy Particle	γ	β^-	β^+	α	n	SF*	P	e^-	X-ray
80-Hg-206	4.98600E+02	417.67	130.04	0	3	3	-	-	-	-	-	12	6
81-Tl-206	2.52120E+02	536.09	2.57	0	3	3	-	-	-	-	-	9	7
81-Tl-206m	2.25600E+02	153.29	2489.48	0	7	-	-	-	-	-	-	24	6
81-Tl-207	2.86200E+02	491.35	3.34	0	2	3	-	-	-	-	-	9	7
81-Tl-207m	1.33000E+00	183.7	1157.41	0	2	-	-	-	-	-	-	9	6
81-Tl-208	1.83600E+02	595.11	3383.55	0	29	17	-	-	-	-	-	78	7
81-Tl-209	1.32000E+02	684.91	2122.21	0	3	1	-	-	-	-	-	12	7
81-Tl-210	7.80000E+01	1092.49	2726.51	0.58	25	13	-	-	1	-	-	44	7
82-Pb-205	4.82831E+14	8.95	59.29	0	-	-	1	-	-	-	-	3	6
82-Pb-209	1.17108E+04	197.34	0	0	-	1	-	-	-	-	-	-	-
82-Pb-210	6.99302E+08	40.72	4.82	0	1	2	-	1	-	-	-	4	2
82-Pb-211	2.16600E+03	449.07	68.45	0	25	11	-	-	-	-	-	44	7
82-Pb-212	3.83040E+04	176.09	145.47	0	6	3	-	-	-	-	-	21	7
82-Pb-214	1.60800E+03	291.06	243.93	0	23	7	-	-	-	-	-	58	7
83-Bi-210	4.33037E+05	387.68	0.68	0.01	2	1	-	2	-	-	-	9	6
83-Bi-210m	9.46728E+13	46.94	261.12	5009.22	12	-	-	8	-	-	-	33	6
83-Bi-211	1.30200E+02	10.06	47.58	6675.34	1	1	-	2	-	-	-	6	6
83-Bi-212	3.63240E+03	502.58	107.26	2216.94	23	7	-	11	-	-	-	65	13
83-Bi-212m	1.50000E+03	133.66	60.48	7423.02	6	7	-	12	-	-	-	22	9
83-Bi-212n	5.40000E+02	1256.9	5.06	0	-	1	-	-	-	-	-	-	-
83-Bi-213	2.73540E+03	444.36	129.2	128.7	6	3	-	2	-	-	-	12	13
83-Bi-214	1.19400E+03	628.55	1539.99	1.17	179	65	-	6	-	-	-	164	13
83-Bi-215	4.44000E+02	750.67	750.67	0	-	-	-	-	-	-	-	-	-
84-Po-209	3.21888E+09	0.44	5.15	4963.74	11	-	1	5	-	-	-	36	14
84-Po-210	1.19567E+07	0	0.01	5407.52	1	-	-	2	-	-	-	6	7
84-Po-211	5.16000E-01	0.16	7.75	7586.14	3	-	-	3	-	-	-	12	7

Nuclide	$T_{1/2}$ (s)	Mean Decay Energies (keV)			Number of Spectral Lines								
		Light Particle	Electro-magnetic	Heavy Particle	γ	β^-	β^+	α	n	SF*	P	e^-	X-ray
84-Po-211m	2.55000E+01	10.07	1489.89	7549.94	4	-	-	4	-	-	-	12	7
84-Po-212	3.00000E-07	0	0	8954.25	-	-	-	1	-	-	-	-	-
84-Po-212m	4.51000E+01	0.38	91.23	11784.5	2	-	-	3	-	-	-	9	7
84-Po-213	4.20000E-06	0	0.02	8536.39	1	-	-	2	-	-	-	6	7
84-Po-214	1.63700E-04	0	0.08	7833.48	2	-	-	3	-	-	-	9	7
84-Po-215	1.78000E-03	0.03	0.22	7525.97	2	1	-	3	-	-	-	7	7
84-Po-216	1.50000E-01	0	0.02	6906.57	1	-	-	2	-	-	-	6	7
84-Po-218	1.85880E+02	0.01	0.01	6113.59	1	1	-	2	-	-	-	6	7
85-At-215	1.00000E-04	0.02	0.19	8178.05	1	-	-	2	-	-	-	6	7
85-At-217	3.23000E-02	0.08	0.3	7199.08	4	1	-	4	-	-	-	6	7
85-At-218	1.50000E+00	52.47	11.86	6803.97	2	1	-	3	-	-	-	6	2
85-At-219	5.40000E+01	17.86	0.05	6195.12	-	1	-	1	-	-	-	-	-
86-Rn-217	5.40000E-04	0.08	0.15	7884.18	1	-	-	2	-	-	-	6	7
86-Rn-218	3.50000E-02	0.01	0.76	7261.77	1	-	-	2	-	-	-	6	7
86-Rn-219	3.96000E+00	6.67	55.29	6884.88	16	-	-	11	-	-	-	12	7
86-Rn-220	5.58000E+01	0.01	0.63	6404.1	1	-	-	2	-	-	-	6	7
86-Rn-222	3.30316E+05	0.01	0.39	5590.01	2	-	-	3	-	-	-	9	7
87-Fr-221	2.94000E+02	8.82	29.82	6471.41	11	-	-	14	-	-	-	21	7
87-Fr-223	1.30800E+03	379.1	58.99	0.33	106	21	-	1	-	-	-	135	7
88-Ra-223	9.87552E+05	74.74	134.29	5781.65	47	-	-	25	-	-	-	86	7
88-Ra-224	3.14496E+05	2.35	10.43	5776.03	5	-	-	5	-	-	-	18	7
88-Ra-225	1.27872E+06	107.8	13.83	0	1	2	-	-	-	-	-	4	2
88-Ra-226	5.06477E+10	3.9	7.3	4859.36	5	-	-	5	-	-	-	18	7
88-Ra-228	1.81456E+08	21.47	2	0	5	5	-	-	-	-	-	9	2
89-Ac-225	8.64000E+05	27.61	17.15	5868.42	51	-	-	42	-	-	-	129	7
89-Ac-227	6.87104E+08	14.81	0.56	69.33	30	3	-	19	-	-	-	17	4
89-Ac-228	2.21400E+04	440.18	963.25	0	164	38	-	-	-	-	-	67	7
90-Th-227	1.61724E+06	49.31	110.07	6017.13	239	-	-	58	-	-	-	394	7
90-Th-228	6.03590E+07	20.48	3.08	5497.53	14	-	-	9	-	-	-	43	7
90-Th-229	2.31633E+11	115.9	90.31	4947.01	49	-	-	26	-	-	-	95	7
90-Th-230	2.37944E+12	12.4	1.28	4747.43	8c	-	-	7	0c	0	-	26	7

Nuclide	$T_{1/2}$ (s)	Mean Decay Energies (keV)			Number of Spectral Lines								
		Light Particle	Electro-magnetic	Heavy Particle	γ	β^-	β^+	α	n	SF*	P	e^-	X-ray
90-Th-231	9.18720E+04	164.94	25.82	0	47	13	-	-	-	-	-	122	7
90-Th-232	4.43384E+17	13.03	1.24	4077.42	2c	-	-	3	0c	0	-	8	7
90-Th-233	1.33800E+03	412.18	37.49	0	120	27	-	-	-	-	-	334	7
90-Th-234	2.08138E+06	60.56	8.8	0	12	5	-	-	-	-	-	24	7
90-Th-235	4.14000E+02	640	640	0	-	-	-	-	-	-	-	-	-
91-Pa-231	1.03383E+12	52.3	38.73	5061.31	75c	-	-	23	0c	0	-	150	7
91-Pa-232	1.13184E+05	168.15	936.41	0	42	10	1	-	-	-	-	112	14
91-Pa-233	2.33280E+06	196.33	215.79	0	19	5	-	-	-	-	-	50	7
91-Pa-234	2.44080E+04	385.92	1434.57	0	369	56	-	-	-	-	-	938	7
91-Pa-234m	7.02000E+01	816.5	19.74	0	126	23	-	-	-	-	-	290	9
91-Pa-235	1.45200E+03	464.14	9.87	0	10	1	-	-	-	-	-	33	7
92-U -232	2.20272E+09	16.84	1.69	5397.04	15c	-	-	9	0c	0	-	41	7
92-U -233	5.02555E+12	7.6	1.23	4904.13	116	-	-	37	-	-	-	235	7
92-U -234	7.75370E+12	14.14	1.45	4841.98	6c	-	-	5	0c	0	-	8	7
92-U -235	2.22102E+16	50.67	163.62	4464.6	50c	-	-	17	0c	0	-	138	7
92-U -235m	1.56000E+03	0.08	0	0	1	-	-	-	-	-	-	1	-
92-U -236	7.47915E+14	11.06	1.2	4571.65	2c	-	-	3	0c	0	-	6	2
92-U -237	5.83200E+05	199.68	143.38	0	23	5	-	-	-	-	-	59	7
92-U -238	1.40999E+17	10.21	1.10	4258.77	2c	-	-	3	0c	0	-	6	2
92-U -239	1.40820E+03	409.91	51.57	0	153	32	-	-	-	-	-	132	7
92-U -240	5.07600E+04	145.43	9.26	0	2	2	-	-	-	-	-	6	2
93-Np-236	4.79675E+12	239.6	152.99	8.11	11	1	2	1	-	-	-	33	14
93-Np-236m	8.10000E+04	91.41	49.13	0	6	2	3	-	-	-	-	20	9
93-Np-237	6.75333E+13	69.86	33.52	4862.73	51	-	-	16	-	-	-	125	7
93-Np-238	1.82909E+05	232.46	644.32	0	28	8	-	-	-	-	-	83	7
93-Np-239	2.03472E+05	262.84	182.19	0	33	8	-	-	-	-	-	89	7
93-Np-240	3.90000E+03	466.83	1246.77	0	32	1	-	-	-	-	-	34	7
93-Np-240m	4.44000E+02	682.96	336.8	0	80	24	-	-	-	-	-	59	9
93-Np-241	8.34000E+02	437.22	36.09	0	14	7	-	-	-	-	-	33	7
94-Pu-236	9.01916E+07	13.39	1.58	5852.38	27c	-	-	13	0c	0	-	82	7
94-Pu-237	3.91392E+06	17.5	55.16	0.23	38	-	6	8	-	-	-	100	14

Nuclide	$T_{1/2}$ (s)	Mean Decay Energies (keV)			Number of Spectral Lines								
		Light Particle	Electro-magnetic	Heavy Particle	γ	β^-	β^+	α	n	SF*	P	e^-	X-ray
94-Pu-238	2.76754E+09	11.19	1.55	5579.8	34c	-	-	15	0c	0	-	101	7
94-Pu-239	7.60948E+11	7.93	0.73	5237.73	221c	-	-	59	0c	0	-	558	7
94-Pu-240	2.07108E+11	11.12	1.36	5243.03	7c	-	-	6	0c	0	-	22	7
94-Pu-241	4.52220E+08	5.24	0	0.12	14	1	-	11	-	-	-	33	7
94-Pu-242	1.17868E+13	9.38	1.29	4973.33	3c	-	-	4	0c	0	-	10	7
94-Pu-243	1.78416E+04	173.65	25.08	0	19	9	-	-	-	-	-	50	7
94-Pu-244	2.52461E+15	7.71	9.76	4872.51	1c	-	-	2	0c	0	-	4	2
94-Pu-245	3.78000E+04	331.43	398.58	0	82	20	-	-	-	-	-	98	7
94-Pu-246	9.37440E+05	114.88	123.78	0	13	2	-	-	-	-	-	32	7
95-Am-240	1.82880E+05	82.95	1031.27	0.01	33	-	15	3	-	-	-	37	7
95-Am-241	1.36581E+10	39.08	27.51	5557.44	185c	-	-	53	0c	0	-	372	7
95-Am-242	5.77440E+04	182.68	16.7	0	2	2	2	-	-	-	-	9	9
95-Am-242m	4.44962E+09	45.95	4.18	24.78	82c	-	-	17	0c	0	-	208	9
95-Am-243	2.32416E+11	23.93	56.97	5358.99	18c	-	-	12	0c	0	-	46	7
95-Am-244	3.63600E+04	308.1	843.4	0	7	1	-	-	-	-	-	19	7
95-Am-244m	1.56000E+03	503.89	12.44	0	3	4	1	-	-	-	-	7	9
95-Am-245	7.38000E+03	284.73	27.74	0	6	3	-	-	-	-	-	19	7
95-Am-246	2.34000E+03	715.34	775.2	0	14	1	-	-	-	-	-	40	7
95-Am-246m	1.50000E+03	484.6	1016.11	0	143	35	-	-	-	-	-	220	7
96-Cm-241	2.83392E+06	140.84	496.76	60.29	47	-	7	11	-	-	-	132	14
96-Cm-242	1.40772E+07	10.17	1.37	6206.48	29c	-	-	16	0c	0	-	82	7
96-Cm-243	9.46728E+08	139.22	133.17	5940.45	27	-	1	28	-	-	-	59	14
96-Cm-244	5.68037E+08	8.87	1.21	5893.66	19c	-	-	9	0c	0	-	43	7
96-Cm-245	2.68240E+11	81.29	93.8	5448.34	12	-	-	8	-	-	-	33	7
96-Cm-246	1.49267E+11	8.2	3	5514.3	1c	-	-	2	0c	0	-	4	2
96-Cm-247	5.04922E+14	22.39	302.8	5028.18	8	-	-	7	-	-	-	23	7
96-Cm-248	1.07296E+13	6.29	579.13	19809.8	1c	-	-	4	0c	0	-	4	2
96-Cm-249	3.84900E+03	283.72	19.68	0	22	7	-	-	-	-	-	63	7
96-Cm-250	2.52461E+11	0	4900	129582	0c	-	-	1	0c	0	-	-	-
97-Bk-249	2.76480E+07	33.04	0.03	0.08	3c	2	-	8	0c	0	-	13	9
97-Bk-250	1.15812E+04	297.05	905.41	0	48	21	-	-	-	-	-	31	7

Nuclide	$T_{1/2}$ (s)	Mean Decay Energies (keV)			Number of Spectral Lines								
		Light Particle	Electro-magnetic	Heavy Particle	γ	β^-	β^+	α	n	SF*	P	e^-	X-ray
98-Cf-249	1.10767E+10	29.85	329.19	5927.56	34c	-	-	31	0c	0	-	74	7
98-Cf-250	4.12773E+08	5.96	6.34	6262.16	3c	-	-	4	0c	0	-	10	7
98-Cf-251	2.83387E+10	181.68	120.26	5877.87	20	-	-	14	-	-	-	52	7
98-Cf-252	8.34698E+07	6.01	217.38	11805.3	3c	-	-	5	0c	0	-	10	7
98-Cf-253	1.53878E+06	80.46	0.08	18.82	3	2	-	2	-	-	-	10	4
99-Es-253	1.76861E+06	4.56	1.08	6733.63	65c	-	-	26	0c	0	-	143	7

* A zero in this column indicates the presence of spontaneous fission fragment data - no spectral data are specified (only mean energies) for the SF fragments in ENDF-6 format.

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