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Invited review

Decay data: review of measurements, evaluations and compilations

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Abstract

Decay data represent an important means of characterising and quantifying radioactive material, as well as providing an important route to our understanding of the structure of the nucleus. The principle decay parameters are defined in this review, prior to undertaking an applications-based assessment of the most relevant contemporary measurements, evaluations and compilations. Emphasis has been placed on the demands of a series of IAEA Co-ordinated Research Programmes that focus on decay data and gamma-ray standards. Some of the more important decay-data issues are also reviewed with respect to recent measurements that address the anomalies associated with intermediate- and long-lived radionuclides. Short-lived fission products pose significant characterisation problems due to their high degree of instability, although a combination of mass separation and complex detector arrays has resulted in rapid analyses and major advances in our understanding of their nuclear properties and structure. Finally, a select number of decay-data evaluations and compilations are discussed in terms of the powerful manipulation and communication capabilities of PCs, CD-ROMs and the Internet.

Keywords: Decay modes; Nuclear decay data; Decay-data libraries; Nuclear data centres; Measurements; Evaluations and compilations

1. Introduction

Decay data are defined as those parameters relating to the normal radioactive decay modes of a nuclide, and include:

half-life,
total decay energies (Q-values) and branching fractions,
alpha-particle energies and emission probabilities,
beta-particle energies, emission probabilities, and transition types,
electron-capture (and positron) energies, transition probabilities, and transition types,
gamma-ray energies, emission probabilities and internal conversion coefficients,
Auger and conversion-electron energies and emission probabilities,
X-ray energies and emission probabilities,
characteristics of spontaneous fission (branching fraction(s) and recoil energies, while setting aside the physics associated with the mass and nuclear-charge distributions of the resulting fragments),
delayed-neutron energies and emission probabilities,
delayed-proton energies and emission probabilities.

Over recent years, more exotic modes of decay have been detected with increasing regularity, specifically the emission of nuclear clusters (such as Ne and Mg nuclei from ^{234}U, and ^{30}Mg nuclei from ^{236}U) and double beta decay. These more complex and low-probability entities are only addressed briefly in a review that focuses heavily on α, β^-, β^+, electron-capture and gamma-ray decay.

The complex nuclear features of radioactive decay are well documented elsewhere, and the reader is referred to

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a series of textbooks and other notable publications that provide more detailed descriptions of the nucleus and related decay processes than are considered in this review (Krane, 1988; Das and Ferbel, 1994; Burcham and Jobes, 1995; Helmer, 1996; Hodgson et al., 1997; Cottingham and Greenwood, 1998; Longworth et al., 1998; Heyde, 1999; Povh et al., 1999). Experimental procedures and measurement techniques have developed over many years to detect and characterise the various decay processes and follow the behaviour of the daughter products. Laboratory studies are many and varied, and their usage will only be mentioned in a peripheral manner within a review that focuses on the present demands for decay data. A number of dedicated texts have been published on radiation detectors, and queries concerning such hardware are best addressed through these references (Mann et al., 1980; Glover, 1984; Debertin and Helmer, 1988; Gilmore and Hemingway, 1995; Poenaru and Greiner, 1997; Knoll, 2000).

Radionuclidic decay data are used in many types of non-nuclear application (e.g., chemical, paper, petroleum, automotive, electronic, metallurgical and mining industries), medical treatments and functional studies, life sciences and environmental monitoring, improving productivity, quality control, health and safety. Density, thickness and moisture gauges are based on the attenuation of radioactive emissions, while specific medical procedures involve the use of radionuclides including the radiolabelling of DNA and pharmaceuticals for functional studies. Accurate and reliable decay data are required to guarantee the precision and efficacy of a wide range of radioactive products, including medical studies and research-based advances.

Users of decay data would prefer to adopt recommended data sets or libraries so that they can concentrate fully on the various applications and calculational validity of their work. Hence, both comprehensive and dedicated decay-data files have been assembled for use in the nuclear power industry, fuel reprocessing and waste management, and for more general application and basic nuclear research. These libraries of recommended data are based on evaluations of published measurements that have been brought together to derive partial and complete decay schemes for individual nuclides. Inconsistencies between the various measurements may occur, but normally every effort is made to resolve such difficulties or advise upon the need for additional measurements of the decay parameters. The Table of Isotopes represents a good example of a comprehensive tabulation of decay data and nuclear structure in hard-copy form and CD-ROM (Firestone et al., 1996, 1998), while Lagoutine et al. (1982–1987) and Bé et al. (1999a–c) have focused their attention on the decay data of a much smaller number of the more important radionuclides to provide extensive tabulations of their recommended decay data and descriptions of the evaluation procedures. Both approaches are highly valued, and provide the user with the desired decay data at differing levels of detail.

Brief descriptions are given below of the natural modes of radioactive decay, followed by efforts to identify inadequacies in the quantitative definition of specific data. Measurements have been made or are underway to address and remove these anomalies, as described in some detail. Finally, the growth of Internet usage is noted, along with the consequences with respect to the handling of recommended decay-data libraries.

2. Decay-data parameters

All nuclides consist of atoms with a central, heavy and positively-charged nucleus surrounded by a series of orbiting shells of light, negatively-charged electrons. When the negative charge of the electrons equals the positive charge on the nucleus, the atom is neutral. Protons and neutrons make up the nucleus, and are collectively known as nucleons; the proton carries a positive charge equal in magnitude but opposite in sign to that of the electron, while the neutron has no associated charge.

Radioactive decay occurs as a consequence of the relative values of a number of basic nuclear parameters. The total number of protons in a given nucleus is known as the atomic number (Z), and the total number of nucleons in a given nucleus is defined as the mass number ($A = N + Z$), where N is the total number of neutrons in the same nucleus. However, the measured mass of any nucleus is slightly less than the constituent sum of the nucleons, which is referred to as the mass defect (normally expressed in energy units via Einstein's equation, $E = mc^2$). This energy is the nuclear binding energy that holds the nucleons together.

Atoms of a given element have the same number of protons in the nucleus but differing numbers of neutrons, and have historically been called isotopes. Nuclide has become a more acceptable term, while radionuclide refers to any radioactive nuclear species. Isomers are radionuclides that have the same atomic and mass numbers, but differing nuclear binding energies and hence different energy states; the lowest energy state is the ground state, while states of higher energy are called excited states (and the longer-lived isomeric states are referred to as metastable isomers).

Only about 275 of approximately 3000 known nuclides are stable, and do not undergo radioactive decay. Almost 60% of the stable nuclides contain even

numbers of both protons and neutrons (even–even nuclei), while the remaining 40% are almost equally divided between an even number of protons and odd number of neutrons (even–odd nuclei) and an odd number of protons and even number of neutrons (odd–even nuclei). Greater stability is achieved with ensembles of pairs of like nucleons. The light, stable nuclides (below $Z = 10$) have $N/Z = 1$, while N/Z increases to $\sim$1.5 for heavier nuclides up to bismuth ($Z = 83$). Nuclide stability depends on this N/Z ratio and the pairing of nucleons.

Stable nuclides are plotted as black squares, while known unstable radionuclides are depicted as open squares in Fig. 1. A line of stability arises from such a plot, with neutron-deficient nuclides containing the higher numbers of protons (higher atomic numbers) and neutron-rich nuclides possessing the higher numbers of neutrons. Changes in the atomic and neutron numbers for the main and ancillary decay modes are shown in Figs. 2 and 3, respectively. Each square represents a different radionuclide arranged in order of increasing atomic number (Z) and neutron number (N). For example, when a radionuclide undergoes β^- decay, Z increases by one and N decreases by one; β^-n decay results in an increase of Z by one, while N decreases by two; α decay produces a reduction of both Z and N by two.

2.1. Half-life

Radioactive decay is largely insensitive to conditions outside the nucleus (although not always so), and the resulting behaviour can be characterised by fixed modes of decay, transition energies and probabilities. The number of atoms decaying per unit time is the activity (A) given by the equation:

$$A = N\lambda = -\mathrm{d}N/\mathrm{d}t$$

where N is the number of atoms at time t, λ is the decay constant (probability that an atom will decay in unit time), and $\mathrm{d}N$ is the number of spontaneous nuclear transitions from that energy state in time interval $\mathrm{d}t$. Activity is expressed in Becquerels (Bq) in which 1 Bq is one disintegration per second (dps). Integration of the above equation and substitution results in the expression:

$$N = N_0 \mathrm{e}^{-\lambda t}$$

where N_0 is the number of atoms at time $t = 0$. Each radionuclide has a characteristic decay constant that is related to the half-life ($t_{1/2}$), the time taken for the number of original radionuclides to reduce by a factor of two:

$$t_{1/2} = \ln 2/\lambda$$

The half-life of a radionuclide is a primary parameter in any radioactive decay process.

2.2. Decay modes

Nuclides with high N/Z ratios are neutron rich, and undergo radioactive decay to reduce this value by the emission of an electron (representing the conversion of a

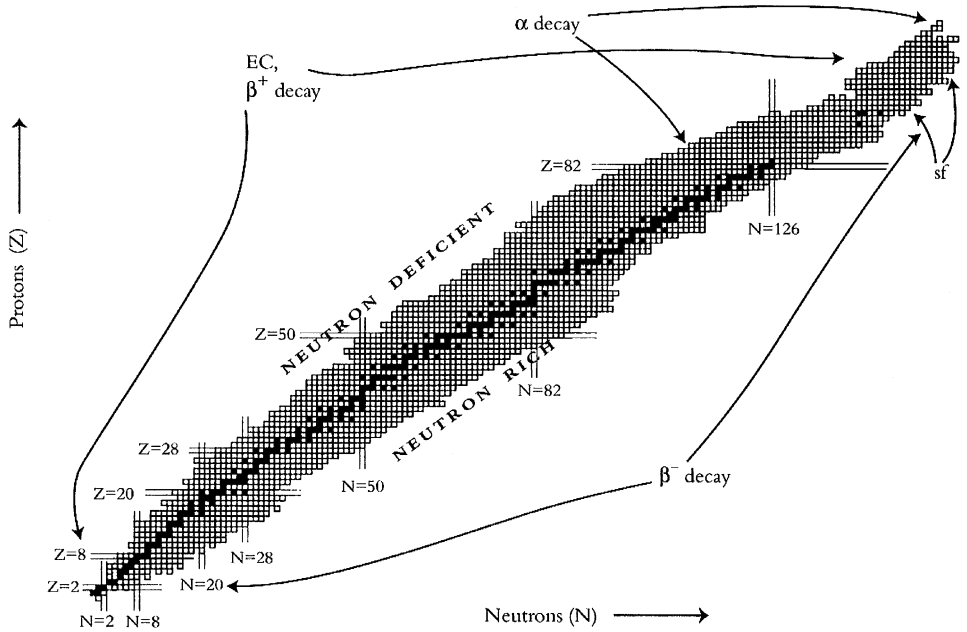

Fig. 1. Nuclear chart: approximate ranges of main decay modes for radionuclides (open squares) with respect to the line of stability; black squares represent stable nuclides.

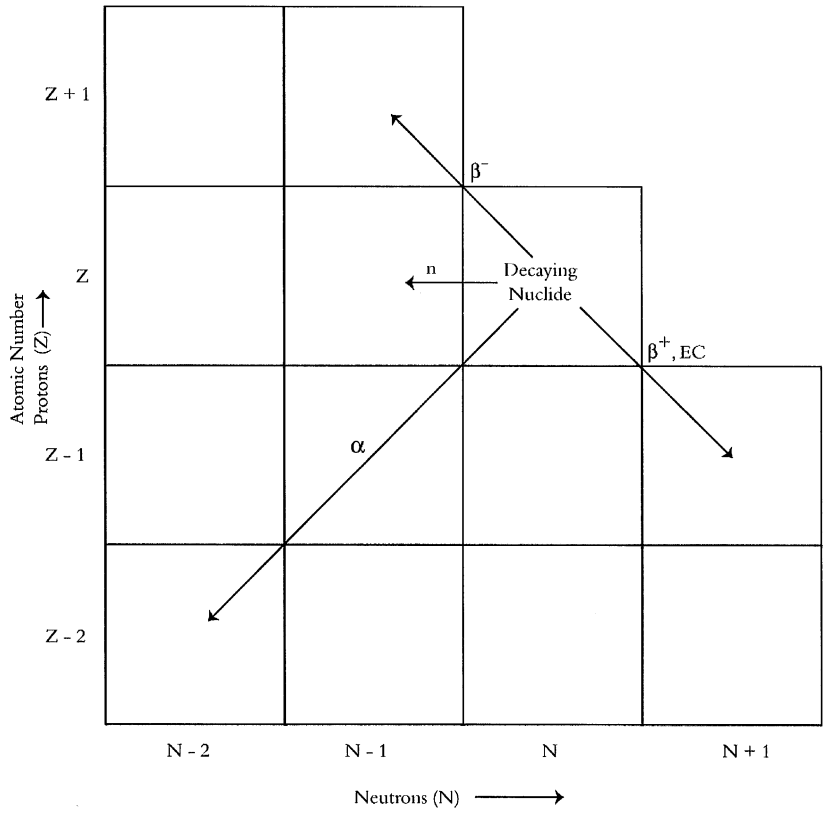

Fig. 2. Main decay modes outlined on a section of the Chart of the Nuclides.

neutron to a proton within the nucleus). Conversely, nuclides with low N/Z ratios will decay by the emission of a positron (representing the conversion of a proton to a neutron); electron capture decay is an alternative process to positron emission, in which the unstable nucleus captures an orbiting electron to produce the same daughter nuclide.

Alpha decay becomes a dominant process above $Z = 80$, with the emission of an alpha particle (helium nucleus). Other relatively common modes of decay include isomeric transition (gamma-ray decay from a well-defined energy state of a radionuclide to a lower energy state in the same nuclide), spontaneous fission and delayed-neutron emission.

2.2.1. Beta decay

The mass number remains unchanged, and the atomic number Z increases by one unit when a radionuclide undergoes β^- decay. An electron and an antineutrino are emitted, as a neutron in the nucleus is transformed into a proton:

$$n \rightarrow p + \beta^- + \bar{v}$$

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + \beta^- + \bar{v}$$

The maximum β energy is represented by the equation:

$$E_{\beta^-_{max}} = Q^- - E_l$$

where Q^- is the overall disintegration energy, equal to the difference in atomic masses between the ground states of the parent and daughter, and E_l is the energy level to which the decay occurs. Similarly, β^+ decay is described by

$$p \rightarrow n + \beta^+ + v$$

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + \beta^+ + v$$

$$E_{\beta^+_{max}} = Q^+ - 2m_0c^2 - E_l$$

where v is a neutrino, Q^+ is the overall disintegration energy, and

$$2m_0c^2 = 1.021998\ \text{MeV}$$

in which m_0 is the mass of an electron at rest. β^+ emission occurs when

$$Q^+ - E_i > 2m_0c^2 \quad \text{(see Section 2.2.2)}.$$

The β transition energy is shared between the electron (or positron) and antineutrino (or neutrino), as a continuous distribution for the two particles extending

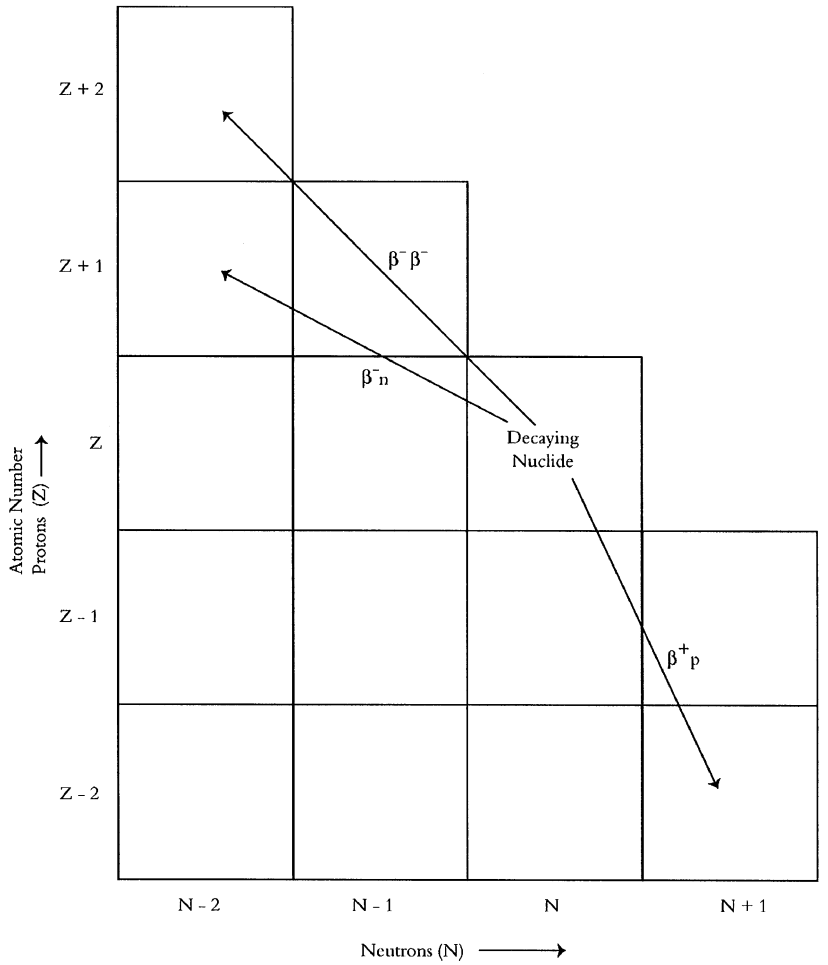

Fig. 3. Ancillary decay modes outlined on a section of the Chart of the Nuclides.

from 0 up to $E_{\beta_{\max}}$. The mean energy can be represented by the equation

$$\bar{E} = \int_0^{E_{\beta_{\max}}} E\, N(E)\mathrm{d}E \Big/ \int_0^{E_{\beta_{\max}}} N(E)\mathrm{d}E$$

where $N(E)\mathrm{d}E$ is the number of β particles with energy between E and $E+\mathrm{d}E$.

The initial and final nuclear states have well-defined total angular momenta with quantum numbers J_i and J_f. The electron-neutrino pair can carry off orbital angular momentum with quantum number L_β, as well as intrinsic spin S_β of 1, -1 or 0. The conservation of the total angular momentum requires

$$J_\mathrm{i} = J_\mathrm{f} + L_\beta + S_\beta$$

$$\Delta J = J_\mathrm{i} - J_\mathrm{f}$$

and the parity relationship is defined as

$$\pi_\mathrm{f}\pi_i = (-1)^{L_\beta}.$$

Allowed transitions have $L_\beta = 0$, while nth order forbidden transitions have $L_\beta = n$.

Selection criteria can be derived for the classification of β transition types, as shown in Table 1. The shape factor for unique forbidden transitions can be calculated as a function of energy. However, some matrix elements are unknown for non-unique forbidden transitions, and the shape factor cannot be determined.

2.2.1.1. Comparative half-life (log ft). Information on the shape factor of a β transition and on level spins and parities can be derived from the comparative partial half-lives (expressed as *ft*) with

$$\left(t_{1/2}\right)_i = \frac{t_{1/2}}{P_{\beta_i}} = \frac{\ln 2}{\lambda_i}$$

where $\left(t_{1/2}\right)_i$ is the partial half-life, $t_{1/2}$ is the half-life in seconds, P_{β_i} is the probability of the transition, and λ_i is the decay constant of the transition. Fermi integrals can

Table 1
Classification of β-transitions

Type	Forbiddenness	ΔJ	$\pi_f\pi_i$
Super-allowed		0	+1
Allowed		$0, \pm 1$	+1
Forbidden unique	First	± 2	−1
	Second	± 3	+1
	Third	± 4	−1
	Fourth	± 5	+1
Forbidden non-unique	First	$0, \pm 1$	−1
	Second	± 2	+1
	Third	± 3	−1
	Fourth	± 4	+1

Table 2
Log *ft* for specific transition types

Type of transition	log *ft*	Mean (log *ft*)
Super-allowed	3.1–3.6	3.4
Allowed	3–10	~5.9
First-forbidden non-unique	5–19	7.3
Second-forbidden non-unique	10.5–14	12.5
First-forbidden unique	7.5–13	9.5
Second-forbidden unique	14–18	15.6
Forbiddenness higher than second	>17	—

be solved to give the following:

$$f_0 t = \frac{2\pi^3 \ln 2}{g^2 C_0} \text{ for an allowed transition,}$$

$$f_n t = \frac{2\pi^3 \ln 2}{g^2 \eta^2} \text{ for a forbidden transition.}$$

Although the function f_n can only be calculated for unique transitions, $C_n \cong C_0$ is assumed for non-unique forbidden transitions, and *ft* can be determined.

Log *ft* values are normally tabulated rather than *ft*, and this parameter varies from 3.4 for super-allowed transitions to above 20 for fourth-forbidden transitions (Table 2; Singh et al., 1998).

2.2.2. Electron capture decay

An orbital electron can be captured by the nucleus:

$$p + e^- \rightarrow n + v$$

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + v$$

A proton is transformed into a neutron, and the atomic number decreases by one. The capture process is accompanied by the emission of a monoenergetic neutrino of energy q_x (x=K, L, M etc.)

$$q_x = Q^+ - E_l - E_x$$

where Q^+ is the decay energy, E_l is the energy of the nuclear level to which electron capture occurs, E_x is the binding energy of the electron in the X shell (or the sub-shell) in the initial atom, and $(Q^+ - E_l)$ is the transition energy.

Electron capture decay can occur when

$$Q^+ - E_l \geqslant E_x,$$

while for $Q^+ - E_l \gg E_x$

electron capture is far more probable in the K shell than in other shells. Furthermore, for

$$Q^+ - E_l \geqslant 2m_0c^2.$$

β^+ emission competes with electron capture decay. Relative capture probabilities for an electron-capture transition (ε) of probability P_ε sum to unity:

$$P_K + P_L + P_M + P_N + \cdots = 1.$$

Recoil occurs, but is generally very small and is ignored (apart from low-mass nuclei).

The probability of capture per unit time in the K shell of an allowed transition is given by

$$\lambda_K = \frac{g^2 |M_{0,1}|^2}{4\pi^2} q_K{}^2 \, g_K{}^2 \, B_K$$

and similar expressions can be formulated for the L_1 and L_2 sub-shells based on $q_{L1}{}^2$ and $q_{L2}{}^2$ respectively, in which

$|M_{0,1}|^2$ is the nuclear matrix element,
q_K, q_{L1}, q_{L2} are neutrino energies,
g_K, g_{L1}, g_{L2} are components of the electron radial wave functions, and
B_K, B_{L1}, B_{L2} are exchange factors.

The exchange factor (B) incorporates two effects: incomplete recovery of the initial and final atomic states due to the change in charge of the nucleus, and the exchange effect which varies because capture in a shell can be achieved by several processes that are not experimentally distinguishable. Recovery and exchange effects have opposite signs and partially counteract each other: while the recovery effect has greater impact for low atomic numbers, the exchange effect dominates for high atomic numbers.

Capture probabilities P_K, P_L, $P_{L1}, \ldots$ can be calculated from known ratios:

$$\frac{P_L}{P_K} = \frac{P_{L1}}{P_K}\left[1 + \frac{P_{L2}}{P_{L1}}\right]$$

$$\frac{P_{L1}}{P_K} = \frac{g_{L1}{}^2}{g_K{}^2}\frac{q_{L1}{}^2}{q_K{}^2} X^{L_1/K}, \quad \text{where } X^{L_1/K} = \frac{B_{L1}}{B_K}$$

$$\frac{P_{L2}}{P_{L1}} = \frac{f_{L2}{}^2}{g_{L1}{}^2}\frac{q_{L2}{}^2}{q_{L1}{}^2}\frac{B_{L2}}{B_{L1}} \cong \frac{f_{L2}{}^2}{g_{L1}{}^2}\frac{B_{L2}}{B_{L1}}$$

and a similar approach can be adopted for the M-shell capture probabilities of M_1 and M_2.

More general expressions can be written for captures in the lower shells:

$$\frac{P_{MN}}{P_L} = \frac{P_{MN}}{P_{L1}} \frac{P_{L1}}{P_L}$$

$$\frac{P_{MN}}{P_{L1}} = \frac{P_{M1}}{P_{L1}} \left[1 + \frac{P_{M2} + P_{N1} + P_{N2} + \cdots}{P_{M1}} \right]$$

and similar equations can be defined for unique forbidden transitions involving K-shell capture. Capture probabilities in the L_1 and L_2 sub-shells can be obtained in a similar manner, along with the contribution due to capture in the L_3 sub-shell.

Log ft values for electron-capture transitions can be calculated in a similar manner to those of β transitions.

2.2.2.1. ε/β^+ ratio. When electron capture competes with β^+ emission, ε/β^+ (or $P_\varepsilon/P_{\beta^+}$) is given by the equation

$$\frac{\varepsilon}{\beta^+} = \frac{\varepsilon}{\beta^+} [P_K + P_L + P_M + \cdots]$$

$$\frac{\varepsilon}{\beta^+} = \frac{\varepsilon P_K}{\beta^+} \left[1 + \frac{P_L}{P_K} + \frac{P_M}{P_K} + \cdots \right]$$

Defining εP_K as ε_K:

$$\frac{\varepsilon_K}{\beta^+} = \frac{\pi}{2} \frac{{q_K}^2 {g_K}^2 B_K}{f_0} \text{ for allowed transitions,}$$

$$\frac{\varepsilon_K}{\beta^+} = \frac{\pi}{2} \frac{{q_K}^{2\Delta J} {g_K}^2 B_K}{f_{\Delta J-1}} \text{ for unique forbidden transitions.}$$

2.2.3. Alpha decay

A nucleus of atomic number Z and mass number A disintegrates by the emission of an α particle to give a daughter nucleus with atomic number $Z-2$ and mass number $A-4$:

$${}^A_Z X_N \rightarrow {}^{A-4}_{Z-2} Y_{N-2} + {}^4_2 \mathrm{He}_2.$$

The α disintegration energy can be represented by the equation:

$$Q_\alpha = E_{\alpha_l} + E_l + E_{rl}$$

where E_{α_l} is the energy of the emitted α particle, E_l is the nuclear-level energy of the daughter nuclide, and E_{rl} is the recoil energy:

$$E_{rl} = \frac{M_\alpha}{M_N + M_\alpha} (Q_\alpha - E_l)$$

in which M_N is the mass of the recoiling daughter nucleus, and M_α is the mass of the α particle. The α particle is held within the nucleus by the Coulomb potential barrier, and has a probability of escaping from the nucleus by means of a tunnelling mechanism. Alpha-particle decay constants can be adequately described by the equation:

$$\log (t_{1/2})_i = AQ^{-1/2} + B$$

where $(t_{1/2})_i$ is the partial half-life of the transition, Q is the total energy of the transition, and A and B are constants calculated on the basis of Q and ground-state transition probabilities.

The hindrance factor (F) for a given α transition is defined by the ratio:

$$F = \frac{(t_{1/2})_{i\,exp}}{(t_{1/2})_{i\,th}}$$

where $(t_{1/2})_{i\,exp}$ is the experimental partial half-life calculated from the emission probability of the α transition, and $(t_{1/2})_{i\,th}$ is the theoretical partial half-life. All even–even transitions between ground states are defined as $F = 1$. The hindrance factor increases with the energy of the excited level of the daughter nuclide. Some transitions of even–odd and odd–odd nuclei that do not populate the ground state exhibit a low hindrance factor. They are "favoured" and correspond frequently to a transition between the initial and final states with identical spins and parities.

2.2.4. Gamma transitions

A gamma transition occurs when a nucleus in an excited state de-excites to a lower energy level, leading to the emission of a γ ray and conversion electron (and an electron–positron pair when energy conditions permit). The γ transition probability is defined by

$$P_{TP} = P_\gamma + P_{ce} + P_e{}^\pm$$

where P_γ, P_{ce} and $P_e{}^\pm$ are the γ-ray, conversion-electron and electron–positron pair emission probabilities, respectively. The energy of the emitted γ ray can be represented by the equation:

$$E_\gamma = (E_i - E_f) - E_r$$

where $E_i - E_f$ is the energy difference between the initial and final levels of the γ transition, and E_r is the recoil energy of the nucleus in the final state:

$$E_r = \frac{(E_\gamma)^2}{2 M_N c^2}$$

where M_N is the mass of the recoiling daughter nucleus. The recoil energy is negligible, except for high γ energies and nuclei with low atomic number.

γ transitions can be classified in terms of multipole order, which is a function of the orbital angular momentum and quantum number L carried by the photon: $L = 0$, monopole; $L = 1$, dipole; $L = 2$, quadrupole, etc. If J_i and J_f are the total angular momenta quantum numbers of the initial and final levels connected by the γ transition, the vectorial relationship between the

Table 3
Classification of γ-ray transitions

$L=\lvert J_i-J_f\rvert$	$\pi_f/\pi_i=-1$		$\pi_f/\pi_i=+1$	
	Transition	Admixture	Transition	Admixture
0 ($0\rightarrow 0$)	Forbidden		Forbidden	
0 ($1/2\rightarrow 1/2$)	E1		M1	
0 ($1\rightarrow 1$)	E1	M2	M1	E2
1	E1	M2	M1	E2
2	M2	E3	E2	M3
3	E3	M4	M3	E4
4	M4	E5	E4	M5

angular momenta is given by the formulation:

$$|J_i - J_f| \leqslant L \leqslant |J_i + J_f|$$

Moreover, the angular momentum carried off by the photon cannot be zero, and consequently a $0\rightarrow 0$ transition cannot occur except by internal conversion or internal-pair creation.

γ radiation is divided into electric and magnetic radiations:

> electric radiation (emitted by the oscillation of electrical charges), with a parity change of $(-1)^L$;
> magnetic radiation (caused by the magnetic moment of the nucleus), with a parity change of $(-1)^{(L+1)}$.

A γ transition can be a mixture of two (or sometimes three) multipole transitions. Two transitions in competition will have multipole order 2^L and 2^{L+1}, one electric and the other magnetic (e.g., mixture of M1 + E2). The classification of γ transitions and their possible admixtures are defined in Table 3. Admixtures are characterised by δ^2 [$= E(L+1)/M(L)$ for the $E(L+1)$ to $M(L)$ transitions].

2.2.4.1. Internal conversion. The de-excitation energy of the nucleus can also be transferred directly to an electron (K, L, M. etc.) which is ejected from the atom:

$$E_{ceX} = E_\gamma - E_x$$

where E_x is the binding energy of the electron in the X shell. The internal conversion coefficient of the electron in the K shell is defined as:

$$\alpha_K = P_{ceK}/P_\gamma$$

where P_{ceK} and P_γ are the K conversion-electron and γ-ray emission probabilities, respectively. Similarly

$$\alpha_L = \frac{P_{ceL}}{P_\gamma},\ \alpha_{Li} = \frac{P_{ceL_i}}{P_\gamma}\ (i = 1, 2, 3)$$

with $\alpha_L = \alpha_{L1} + \alpha_{L2} + \alpha_{L3}$,

and $\alpha_{Mi} = \dfrac{P_{ceMi}}{P_\gamma}\ (i = 1, 2, 3, 4, 5)$

The total conversion coefficient is:

$$\alpha_{total} = \alpha_K + \alpha_L + \alpha_M + \cdots = P_{ce}/P_\gamma$$

where P_{ce} is the total conversion-electron emission probability for the related transition.

Various emission probabilities can be calculated from the equations:

$$P_{ce} = \frac{\alpha_{total}}{1+\alpha_{total}} P_{TP}, \qquad P_\gamma = \frac{P_{TP}}{1+\alpha_{total}},$$

$$P_{ce_x} = \frac{\alpha_x}{1+\alpha_{total}} P_{TP_X}\ (x = \mathrm{K, L, M.....})$$

if $P_e^{\pm}$ is ignored. K/L, K/LM and K/LM... represent abbreviations of the following equations:

$$\frac{K}{L} : \frac{P_{ceK}}{P_{ceL}} = \frac{\alpha_K}{\alpha_L},$$

$$\frac{K}{LM} : \frac{P_{ceK}}{P_{ceL} + P_{ceM}} = \frac{\alpha_K}{\alpha_L + \alpha_M},$$

$$\frac{K}{LM\ldots} : \frac{P_{ceK}}{P_{ceL} + P_{ceM} + \cdots} = \frac{\alpha_K}{\alpha_L + \alpha_M + \cdots}$$

Internal conversion depends on the initial state of the electron (atomic shell or sub-shell), the atomic number Z, and the nuclear transition. Values increase with atomic number and multipolarity, and decrease with increasing γ energy to become negligible for high energies.

2.2.4.2. Internal-pair formation. A small fraction of the decay occurs through the creation of an electron–positron pair ($e^{\pm}$) when the γ transition energy exceeds 1022 keV ($2m_0c^2$). The balance of the original transition energy above 1022 keV is expended as kinetic energy imparted to the two resulting particles:

$$E(e^{\pm}) = E_\gamma - 2m_0c^2$$

Internal-pair formation is defined in terms of the ratio of the number of (e^+e^-) pairs formed to the number of gamma rays emitted. Thus, the internal-pair creation coefficient is given by:

$$\alpha_\pi = N_{e^{\pm}}/N_\gamma$$

where $N_e^{\pm}$ is the number of electron–positron pairs created, and N_γ is the number of emitted photons (α_π is of the order of 10^{-3}–10^{-4}). These coefficients increase with increasing gamma-ray energy, but they are normally small in magnitude (although there are some notable exceptions, such as in the decay of ^{24}Na).

2.2.5. Spontaneous and induced fission

Measurable rates of spontaneous fission have only been observed among the heaviest elements (breaking into two fragments of approximately equal mass). While nuclides with $A > 230$ are susceptible to this decay mode (eg., ^{240}Pu, ^{244}Cm and ^{252}Cf), spontaneous fission is normally a minor decay component, as in ^{238}U which is dominated by alpha decay (sf branching fraction of only 5.5×10^{-7}).

Fission may also be induced by bombardment with neutrons, charged particles or gamma rays to create unstable compound nuclei. The nuclide is split into fission fragments, and the process is accompanied by the emission of neutrons and gamma rays. These fission fragments (or fission products) contain an excess of neutrons that is reduced by the emission of prompt neutrons and β^- decay, or through the emission of delayed neutrons after β^- decay, as illustrated by the following example:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}n \rightarrow ^{236}_{92}\mathrm{U} \xrightarrow{sf} ^{90}_{36}\mathrm{Kr} + ^{144}_{56}\mathrm{Ba} + 2^{1}_{0}n$$

prompt neutrons,

$$^{90}_{36}\mathrm{Kr} \xrightarrow{\beta^-} ^{90}_{37}\mathrm{Rb} \xrightarrow{\beta^-} ^{90}_{38}\mathrm{Sr} \xrightarrow{\beta^-} ^{90}_{39}Y \xrightarrow{\beta^-} ^{90}_{40}\mathrm{Zr}$$

stable,

$$^{144}_{56}\mathrm{Ba} \xrightarrow{\beta^-} ^{144}_{57}\mathrm{La} \xrightarrow{\beta^-} ^{144}_{58}\mathrm{Ce} \xrightarrow{\beta^-} ^{144}_{59}\mathrm{Pr} \xrightarrow{\beta^-} ^{144}_{60}\mathrm{Nd}$$

stable.

Another well-characterised fission product is ^{87}Br, which also undergoes β^-n decay to ^{86}Kr:

$$^{87}_{35}\mathrm{Br} \xrightarrow{\beta^-} ^{87}_{36}\mathrm{Kr} \xrightarrow{\beta^-} ^{87}_{37}\mathrm{Rb} \xrightarrow{\beta^-} ^{87}_{38}\mathrm{Sr}$$

$\beta^- \downarrow$ stable,

$^{86}_{36}\mathrm{Kr} + ^{1}_{0}n$ delayed neutron.

stable

Prompt neutron emissions cease immediately after fission has occurred, whereas the delayed-neutron emissions continue over a few hours, depending on the half-life of the fission-product nuclide. The average number of neutrons emitted for each neutron absorbed in a fission reaction is defined as $\bar{v}$; values are not integers because the resulting compound nucleus can split in many different ways.

2.2.6. Delayed emissions

Protons can be emitted from radionuclides that are significantly neutron deficient, while neutron-rich nuclides possess loosely bound neutrons. Under suitable circumstances of decay, either proton or neutron emissions can occur from the excited states of these two extremes. Both types of delayed emission occur from excited states formed by a prior decay process. Thus, delayed neutrons are emitted from the excited states of certain fission products following spontaneous fission (see Section 2.2.5); and the equivalent population of the excited states of neutron-deficient nuclides can result in delayed-proton decay.

Various caesium radionuclides of low mass number undergo β^+ decay to the equivalent excited states of xenon, followed by either delayed-proton emission (β^+p decay) or further direct β^+ decay:

$$^{114}_{55}\mathrm{Cs} \xrightarrow{\beta^+} ^{114}_{54}\mathrm{Xe} \xrightarrow{\beta^+} ^{114}_{53}\mathrm{I} \xrightarrow{\beta^+} ^{114}_{52}\mathrm{Te}\ \text{etc.}$$

$\beta^+ \downarrow$

$^{113}_{53}\mathrm{I} + ^{1}_{1}p$

$\beta^+ \downarrow$ delayed proton

$^{113}_{52}\mathrm{Te}$ etc.

$$^{115}_{55}\mathrm{Cs} \xrightarrow{\beta^+} ^{115}_{54}\mathrm{Xe} \xrightarrow{\beta^+} ^{115}_{53}\mathrm{I} \xrightarrow{\beta^+} ^{115}_{52}\mathrm{Te}\ \text{etc.}$$

$\beta^+ \downarrow$

$^{114}_{53}\mathrm{I} + ^{1}_{1}p$

$\beta^+ \downarrow$ delayed proton

$^{114}_{52}\mathrm{Te}$ etc.

$$^{116}_{55}\mathrm{Cs} \xrightarrow{\beta^+} ^{116}_{54}\mathrm{Xe} \xrightarrow{\beta^+} ^{116}_{53}\mathrm{I} \xrightarrow{\beta^+} ^{116}_{52}\mathrm{Te}\ \text{etc.}$$

$\beta^+ \downarrow$

$^{115}_{53}\mathrm{I} + ^{1}_{1}p$

$\beta^+ \downarrow$ delayed proton

$^{115}_{52}\mathrm{Te}$ etc.

2.2.7. Cluster decay

The spontaneous emission of tightly bound nuclear entities of relatively high mass number may also occur, such as ^{14}C, ^{20}O and ^{24}Ne (Helmer, 1996; Hourany et al., 1997). Groups of nucleons form stable entities that are emitted from the nucleus, although their branching fractions are very small (extremely long half-lives). A relatively small number of these cluster decays are listed in Table 4, along with their half-lives.

This mode of decay has an extremely low probability (generally between 10^{-9} and 10^{-16}), and is particularly challenging to detect against a significant background of alpha particles. The SOLENO spectrometer has been developed at Orsay to deflect the unwanted alpha particles,

Table 4
Partial half-lives of cluster decays

Parent	Cluster	Daughter	$t_{1/2}$ (yr)
^{222}Ra	^{14}C	^{208}Pb	5.1×10^{3}
^{223}Ra	^{14}C	^{209}Pb	2.4×10^{8}
^{224}Ra	^{14}C	^{210}Pb	2.3×10^{8}
^{226}Ra	^{14}C	^{212}Pb	5.3×10^{13}
^{228}Th	^{20}O	^{208}Pb	1.7×10^{13}
^{230}Th	^{24}Ne	^{206}Hg	1.3×10^{17}
^{231}Pa	^{23}F	^{208}Pb	3×10^{8}
^{231}Pa	^{24}Ne	^{207}Tl	2.5×10^{15}
^{234}U	^{28}Mg	^{206}Hg	1.8×10^{18}
^{235}U	^{24}Ne	^{211}Pb	$\sim 9 \times 10^{19}$
^{235}U	^{25}Ne	^{210}Pb	$\sim 9 \times 10^{19}$
^{236}Pu	^{28}Mg	^{208}Pb	1.1×10^{14}

and select and direct the clusters to reach the detector along the focal plane; solid state nuclear track detectors (SSNTD) have also been developed to monitor these emissions because of their insensitivity to low-Z particles.

A number of theorectical models have been applied to the prediction of cluster decay, and the development of the analytical super asymmetric fission (ASAF) approach has successfully unified the competing concepts of cold fission, cluster and α decay (Poenaru et al., 1997). Correlations have also been derived for these decay modes, and estimates can be made of their relative probabilities to shed new light on the parent nucleus (Mikheev and Tretyakova, 1997).

2.2.8. Double beta decay

Nuclide stability towards beta decay arises because the Q_β energy is negative or the decay mode is hindered by the spin-selection rules. However, these factors can be overcome through double β^- decay (Balysh et al., 1994; Helmer, 1996). While the β^- decay of ^{48}Ca is energetically possible, the spins and parities of the parent and daughter states are 0^+ and 6^+ respectively, and reduce the branching fraction of this decay mode virtually to zero. Similarly, ^{76}Ge is extremely stable towards β^- decay on the basis of energy considerations. Relevant decay energies for these two radionuclides are given in Table 5, and show that double β^- decay is feasible.

There are different theoretical explanations for the double β^- decay process that result in the postulated formation of either two or no antineutrinos. Interpretations of this rare decay mode have underlying implications towards the energy distribution of the electrons, and to the development of an all-encompassing theory of nuclear instability.

Table 5
Decay energies for double β^- decay

Parent	Daughter	Q_β (keV)	$Q_{\beta\beta}$ (keV)
$^{48}_{20}Ca$	$^{48}_{22}Ti$	278(5)	4272(10)
$^{76}_{32}Ge$	$^{76}_{34}Se$	−923(1)	2039(2)

2.3. Secondary radiations

Primary radioactive decay is accompanied by secondary radiations that appear as conversion electrons, Auger electrons, X-rays and bremsstrahlung photons:

(a) internal bremsstrahlung associated with both β and electron-capture decay;
(b) internal ionisation and excitation associated with both β and electron-capture decay;
(c) electron rearrangement caused by electron capture and internal conversion (vacancies arise and are accompanied by the emission of an Auger electron or X-ray, and the creation of new vacancies in the peripheral shells by the resulting cascade);
(d) Coster–Kronig transitions when an L_i vacancy ($i=1$, 2) moves towards a lesser bound sub-shell ($L_1 \rightarrow L_2$, $L_1 \rightarrow L_3$, $L_2 \rightarrow L_3$) with the emission of an L_iL_jX-Auger electron ($X=$ M, N. . . .).

2.4. Ancillary decay data

Some of the decay-data requirements within the nuclear power industry involve parameters that can be derived from the discrete data described above. This situation is exemplified by the need in decay-heat calculations for the mean alpha, beta and gamma energy releases per disintegration of the radionuclides ($\bar{E}_\alpha$, $\bar{E}_\beta$ and $\bar{E}_\gamma$). Ideally, the mean energies can be systematically determined from the discrete alpha, beta and gamma transitions and other relevant emissions.

(a) The mean alpha energy is the mean energy of all heavy particles (alpha particles, recoil nuclei, protons, neutrons, and spontaneous fission fragments):

$$\bar{E}_\alpha = \sum_{i}^{\text{all }\alpha} \bar{E}_{\alpha_i} P_{\alpha_i} + \sum_{j}^{\text{all recoil}} \bar{E}_{\text{rj}} P_{\text{rj}} + \sum_{k}^{\text{all protons}} \bar{E}_{\text{pk}} P_{\text{pk}} + \sum_{l}^{\text{all neutrons}} \bar{E}_{\text{nl}} P_{\text{nl}} + \sum_{m}^{\text{fission frag}} \bar{E}_{\text{Fm}} P_{\text{Fm}}$$

where $\bar{E}_{\alpha_i}$, $\bar{E}_{\text{rj}}$, $\bar{E}_{\text{pk}}$, $\bar{E}_{\text{nl}}$ and $\bar{E}_{\text{Fm}}$ are the mean alpha, recoil nucleus, proton, neutron and fission fragment energies of the ith, jth, kth, lth and mth component of each type respectively, and P_{α_i}, P_{rj}, P_{pk}, P_{nl} and P_{Fm} are the corresponding absolute emission probabilities per disintegration.

(b) The mean beta energy is the mean energy of all electron emissions:

$$\bar{E}_\beta = \sum_i^{\text{all } \beta^-} \bar{E}_{\beta_i^-} P_{\beta_i^-} + \sum_j^{\text{all } \beta^+} \bar{E}_{\beta_j^+} P_{\beta_j^+} + \sum_k^{\text{all Auger}} \bar{E}_{\text{Ak}} P_{\text{Ak}} + \sum_l^{\text{all conversion}} \bar{E}_{\text{cel}} P_{\text{cel}}$$

where $\bar{E}_{\beta_i^-}$, $\bar{E}_{\beta_j^+}$, $\bar{E}_{\text{Ak}}$, and $\bar{E}_{\text{cel}}$ are the mean negatron, positron, Auger electron and conversion-electron energies of the ith, jth, kth and lth transition of each type respectively, and $P_{\beta_i^-}$, $P_{\beta_j^+}$, P_{Ak} and P_{cel} are the corresponding absolute emission probabilities per disintegration.

(c) The mean gamma energy includes all the electromagnetic radiation such as gamma rays, X-rays, annihilation radiation and bremsstrahlung:

$$\bar{E}_\gamma = \sum_i^{\text{all } \gamma} \bar{E}_{\gamma_i} P_{\gamma_i} + \sum_j^{\text{all X-rays}} \bar{E}_{\text{Xj}} P_{\text{Xj}} + \sum_k^{\text{all } \beta^+} 1.022\, P_{\beta_k^+} + \sum_l^{\text{all } \beta^+\beta^-} \bar{E}_{\beta_l} P_{\beta_l}$$

where $\bar{E}_{\gamma_i}$ and $\bar{E}_{\text{Xj}}$ are the mean gamma and X-ray energies of the ith and jth transition of each type respectively, and P_{γ_i} and P_{Xj} are the corresponding emission probabilities per disintegration; $\bar{E}_{\beta_l}$ is the mean internal bremsstrahlung energy of the lth beta transition with absolute emission probability P_{β_l}, and $P_{\beta_k^+}$ is the absolute emission probability of positron transition k.

Unfortunately, all components of the mean alpha, beta and gamma energies of the relevant radionuclides have not been experimentally determined, and theoretical data are required to supplement the available discrete data (see also Section 3). As the emissions from these nuclides are characterised in greater detail and their decay-scheme data become defined with increased confidence, these model predictions can be replaced. At present and in the foreseeable future, all extended libraries of nuclear data for decay-heat calculations are and will be carefully assembled combinations of theory and measurements.

Other examples of the manipulation of decay data to generate subsidiary information include the analysis of samples by neutron activation, and safety assessments to quantify the interaction of the various radiations with matter. The latter can involve the determination of range-energy relationships in the absorbing materials, dose–response curves, and the calculation of dose rates for work-place and medical applications.

3. Specific requirements for decay data

An IAEA Co-ordinated Research Programme (CRP) was initiated in 1985 to produce a recommended set of decay data for specific radionuclides identified as appropriate for the calibration of equipment used to measure X- and gamma-ray emissions (see Table 6; IAEA, 1991). While source preparation and source-detector geometry affect the quality of such measurements, accurate quantitative studies also depend upon well-defined efficiency-calibration curves derived from calibrant decay data. Half-lives, and absolute X- and gamma-ray emission probabilities need to be known with good accuracy for these radionuclides, along with the most significant internal conversion coefficients. A recommended list of 36 nuclides evolved under the auspices of the IAEA-CRP, with requests to measure and evaluate some of the desired decay data to a higher level of precision (Lorenz, 1985; Nichols, 1990). Various measurements were undertaken during the course of this programme, and these resulting and earlier data were evaluated to give a recommended data set (IAEA, 1991), including compilations of high-energy gamma rays, and consideration of efficiency calibration using gamma rays from thermal-neutron capture and proton-capture reactions. A number of half-lives (^{22}Na, ^{54}Mn, ^{55}Fe, ^{56}Co, ^{75}Se, ^{137}Cs, ^{133}Ba and ^{155}Eu), X-ray emission probabilities (^{51}Cr, ^{55}Fe, ^{57}Co, ^{58}Co, ^{75}Se, ^{111}In, ^{113}Sn, ^{133}Ba, ^{154}Eu, ^{198}Au and ^{207}Bi) and gamma-ray emission probabilities (^{51}Cr, ^{57}Co, ^{65}Zn, ^{75}Se, ^{133}Ba, ^{198}Au and ^{243}Am) were judged to merit further study at the end of the programme in 1991. This work has continued beyond the early 1990s, primarily by national standards laboratories, and further improvements have occurred that need to be incorporated into the existing IAEA decay-data base.

The earlier IAEA Co-ordinated Research Programme was re-constituted in 1998 to Update X- and Gamma-ray Decay Data for Detector Calibration and Other Applications (Nichols and Herman, 1998; Herman and Nichols, 1999). Specific objectives have been agreed for this new programme:

(i) revise the decay data of 35 radionuclides contained in IAEA-TECDOC-619 (IAEA, 1991), supplemented with 27 additional radionuclides (half-lives, and absolute X-, gamma-ray and alpha-particle emission probabilities),
(ii) compile and evaluate absolute gamma-ray emission probabilities from several nuclear reactions that are appropriate for detector calibration from 10 to 25 MeV,
(iii) analyse low-energy alpha-induced reactions to obtain calibrated intensities of the 4.439 MeV gamma-ray emission from ^{12}C,
(iv) recommend data for coincidence calibration,

Table 6
Standards for detector calibration — status, 1991; comments, 2000

Radionuclide	Data type[a]	Uncertainty achieved by 1991 (%)[b]	Comments
^{22}Na	$t_{1/2}$	0.1	Well-defined decay scheme
	P_γ	0.014	
^{24}Na	$t_{1/2}$	0.03	Well-defined decay scheme
	P_γ	0.0015–0.005	
^{46}Sc	$t_{1/2}$	0.05	Well-defined decay scheme
	P_γ	0.002	
^{51}Cr	$t_{1/2}$	0.03	Two distinct groupings of P_γ measurements: 0.098 and 0.102 for 320 keV transition
	P_X	1.3	
	P_γ	0.5	
^{54}Mn	$t_{1/2}$	0.13	Simple, well-defined decay scheme
	P_X	3	
	P_γ	0.0024	
^{55}Fe	$t_{1/2}$	0.8	X-ray emitter, with simple decay scheme
	P_X	3.5	
^{56}Co	$t_{1/2}$	0.3	Reasonably complex decay scheme derived from well-defined decay data
	P_γ	0.01–0.4	
^{57}Co	$t_{1/2}$	0.03	P_γ for 14.4 keV transition is particularly uncertain
	P_X	0.7	
	P_γ	0.2–1.5	
^{58}Co	$t_{1/2}$	0.1	Well-defined decay scheme
	P_X	3.8	
	P_γ	0.01	
	α_{total}	3	
^{60}Co	$t_{1/2}$	0.03	Well-defined decay scheme
	P_γ	0.006–0.02	
^{65}Zn	$t_{1/2}$	0.11	Few direct measurements of P_γ for 1115 keV transition, but well-defined decay scheme
	P_X	2.3	
	P_γ	0.5	
	α_{total}	3.8	
^{75}Se	$t_{1/2}$	0.2	Uncertainty in P_γ arises from quantifying direct population of ^{75}As ground state
	P_X	7	
	P_γ	0.3–1.2	
	α_{total}	1–7	
^{85}Sr	$t_{1/2}$	0.006	P_γ for 514 keV transition depends on a theoretical estimate of the EC branch directly to the ground state of ^{85}Rb
	P_X	1.4	
	P_γ	0.4	
	α_{total}	12	
^{88}Y	$t_{1/2}$	0.02	Major gamma-ray transitions are well characterised (898.0 and 1836.1 keV)
	P_X	1.3	
	P_γ	0.03–0.3	
	α_{total}	1	
^{93m}Nb	$t_{1/2}$	0.85	IT decay via single gamma-ray transition (30.82 keV), with high internal conversion
	P_X	3.2	
^{94}Nb	$t_{1/2}$	12	Simple, well-defined decay scheme
	P_γ	0.05	
	α_{total}	1	
^{95}Nb	$t_{1/2}$	0.02	Some of the decay-scheme data have been derived by calculation, and further measurements are merited to confirm P_γ and α_{total} of 765.8 keV gamma ray
	P_γ	0.03	
	α_{total}	1–3	
^{109}Cd (^{109m}Ag)	$t_{1/2}$	0.15	Simple, well-defined decay scheme (short-lived daughter ^{109m}Ag)
	P_X	2.0	
	P_γ	0.6	
	α_{total}	2	
^{111}In	$t_{1/2}$	0.02	P_γ calculated from α_{total} and P_β decay to 416.7 keV nuclear level of ^{111}Cd; confirmatory measurements merited
	P_X	2.4	
	P_γ	0.1	
	α_{total}	1.2	

Table 6 (*continued*)

Radionuclide	Data type[a]	Uncertainty achieved by 1991 (%)[b]	Comments
^{113}Sn (^{113m}In)	$t_{1/2}$	0.03	Simple, well-defined decay scheme (short-lived daughter ^{113m}In)
	P_X	0.6	
	P_γ	0.2	
^{125}Sb	$t_{1/2}$	0.06	Complex, well-defined decay scheme
	P_γ	1.0	
^{125}I	$t_{1/2}$	0.02	Simple, well-defined decay scheme
	P_X	2.2	
	P_γ	1.2	
	α_{total}	1.5	
^{134}Cs	$t_{1/2}$	0.03	Well-defined decay scheme
	P_γ	0.1–1.3	
^{137}Cs (^{137m}Ba)	$t_{1/2}$	0.4	Simple, well-defined decay scheme (short-lived daughter ^{137m}Ba)
	P_X	2.9	
	P_γ	0.2	
	α_{total}	0.7	
^{133}Ba	$t_{1/2}$	0.4	Difficult to resolve 79.6 and 81.0 keV gamma-ray transitions
	P_X	1.3	
	P_γ	0.3–0.8	
	α_{total}	5–7	
^{139}Ce	$t_{1/2}$	0.02	Simple, well-defined decay scheme; P_γ calculated from α_{total} and EC decay (100%)
	P_X	2.8	
	P_γ	0.08	
	α_{total}	0.4	
^{152}Eu	$t_{1/2}$	0.2	Extremely complex decay scheme that has been well characterised through a series of extensive P_γ measurements
	P_X	1.6	
	P_γ	0.5	
^{154}Eu	$t_{1/2}$	0.09	Extremely complex decay scheme that has been well characterised through a series of extensive P_γ measurements
	P_X	2.3	
	P_γ	1.0–1.7	
^{155}Eu	$t_{1/2}$	2.5	
^{198}Au	$t_{1/2}$	0.03	Simple, well-defined decay scheme
	P_X	7	
	P_γ	0.5	
^{203}Hg	$t_{1/2}$	0.03	Simple, well-defined decay scheme; P_γ calculated from α_{total} and adopted P_β
	P_X	3	
	P_γ	0.1	
^{207}Bi	$t_{1/2}$	6	Well-defined decay scheme derived from a series of extensive measurements of P_γ and α_{total}
	P_X	5	
	P_γ	0.03–0.6	
	α_{total}	1.4	
^{228}Th decay chain	$t_{1/2}$	0.1–0.9	Well characterised through a series of extensive P_γ measurements
	P_γ	0.2–3	
^{241}Am	$t_{1/2}$	0.15	Complex decay scheme, although there are only two gamma-ray emissions proposed for adoption as standards (26.34 and 59.54 keV)
	P_X	2	
	P_γ	1–4	
^{243}Am/^{239}Np	$t_{1/2}$	0.2	Reasonably well-defined and complex decay scheme; two gamma-ray emissions of ^{243}Am (43.53 and 74.66 keV) and three gamma-ray emissions of ^{239}Np (106.12, 228.18 and 277.60 keV) proposed for adoption as standards
	P_γ	1.5–2	
	α_{total}	2	

[a] $t_{1/2}$ — half-life, P_β — beta-particle emission probability, P_X — X-ray emission probability, P_γ — gamma-ray emission probability, α_{total} — total internal conversion coefficient.

[b] Uncertainties for X- and gamma-ray emission probabilities and internal conversion coefficients apply to the major transitions only, corresponding to the 1σ confidence level.

Table 7
Recommended database for detector calibration and other applications: selected radionuclides (as specified by IAEA-CRP (Herman and Nichols, 1999))

Radionuclide	X- and/or γ-ray standard[a]	Dosimetry standard	Medical applications	Environmental monitoring	Waste management	Safeguards
^{22}Na	P		√			
^{24}Na	P					
^{40}K				√		
^{46}Sc	P					
^{51}Cr	P		√			
^{54}Mn	P			√	√	
^{56}Mn			√			
^{55}Fe	P		√		√	
^{59}Fe			√			
^{56}Co	S					
^{57}Co	P		√			√
^{58}Co	P			√		
^{60}Co	P		√	√	√	√
^{64}Cu			√			
^{65}Zn	P			√	√	
^{66}Ga	S		√			
^{67}Ga			√			
^{68}Ga			√			
^{75}Se	S		√			
^{85}Kr				√		
^{85}Sr	P		√	√		
^{88}Y	P					
^{93m}Nb		√				
^{94}Nb	P					
^{95}Nb	P			√		
^{99}Mo			√			
^{99m}Tc			√			
^{103}Ru			√	√		
^{106}Ru-^{106}Rh			√	√		
^{110m}Ag				√	√	
^{109}Cd	P			√		
^{111}In	P		√			
^{113}Sn	P					
^{125}Sb				√		
^{123m}Te	P					
^{123}I			√			
^{125}I	P	√	√			
^{129}I				√	√	
^{131}I		√	√	√		
^{134}Cs				√		
^{137}Cs	P	√		√	√	
^{133}Ba	S		√			
^{139}Ce	P			√		
^{141}Ce	P			√		
^{144}Ce	P		√	√		
^{153}Sm			√			
^{152}Eu	S			√	√	√
^{154}Eu				√	√	√
^{155}Eu	P			√	√	
^{166m}Ho (^{166}Ho)			√			√
^{170}Tm	P					
^{169}Yb			√			
^{192}Ir		√	√			
^{198}Au	P					

Table 7 (*continued*)

Radionuclide	X- and/or γ-ray standard[a]	Dosimetry standard	Medical applications	Environmental monitoring	Waste management	Safeguards
^{203}Hg	P					
^{201}Tl			√			
^{207}Bi			√			
^{226}Ra[a]		√		√	√	
^{228}Th[b]	P			√		
^{234m}Pa				√	√	
^{241}Am	P			√	√	√
^{243}Am					√	

[a] P: Primary standard for detector efficiency calibration.
S: Secondary standard for detector efficiency calibration.
[b] Also daughters in decay chain.

(v) assess uncertainty correlations in evaluation procedures.

The extended database will contain recommended decay data for the nuclides listed in Table 7, based on the use of these radionuclides as calibrants associated with a wide range of applications including environmental monitoring and medical needs. A number of nuclear reactions were identified as suitable for the generation of gamma-ray standards: ^{19}F(p, $\alpha\gamma$)^{16}O*; ^{12}C(p, p′)^{12}C*; ^{11}B(p, γ)^{12}C*; ^{12}C(α, α')^{12}C*; ^{16}O(p, αp)^{12}C*, and others may be considered (in which * denotes excited nuclei). The development of coincidence-counting techniques also requires an assessment of $\gamma-\gamma$ correlations for ^{24}Na, ^{60}Co, ^{88}Y, ^{152}Eu and ^{207}Bi, and high-energy gamma-ray emissions from proton-capture reactions such as ^{11}B(p, γ)^{12}C*.

Well-defined decay data for actinides and their decay chains have always been deemed important to the nuclear power industry, particularly for the reprocessing of irradiated fuel and the storage of the resulting products and wastes under controlled conditions. A decay-data request list was prepared during the course of another IAEA exercise (IAEA, 1976, 1979) that concluded with the evaluation and recommendation of a definitive set of data (IAEA, 1986). This work programme brought together users and measurers of actinide decay data to review their requirements (primarily of relevance to fission reactors and irradiated fuel management). A substantial amount of the available data at that time did not meet the requirements of users. Furthermore, the quoted accuracy of much of the desired data did not satisfy the needs of those specialists involved in fuel assay, safeguards and standards. An internationally sponsored programme of work was begun in the mid-1970s to improve the status of these data, and the various achievements were reported in 1986 (see Table 8). However, it is worth noting that measurements have continued as a consequence of the reported inadequacies of some of the recommended decay data and the desire for further improvements. Thus, the document issued in 1986 contains the statement that "...several of the identified decay data needs remain unsatisfied" — this situation has improved as laboratories around the world have continued to address some of the specific data issues.

A relatively large number of short-lived fission products contribute significantly to the decay heat generated by irradiated nuclear fuel immediately following the controlled termination of neutron-induced fission. Estimates of decay heat at short cooling times possess the greatest uncertainty because many of the contributing radionuclides are poorly characterised, with partially known (even non-existent) decay schemes that arise from a serious lack of measured data. Under these circumstances, theoretical calculations have been undertaken to derive spectral approximations of beta, gamma and delayed-neutron data from the gross theory of beta decay (Takahashi et al., 1973; Brady and England, 1989; Rudstam and England, 1990). A combination of beta-strength functions and possible gamma-ray cascades can be used to calculate gamma-ray continuum spectra (Katakura and England, 1991), and the resulting data can be checked in some cases against measurements to gain confidence in the procedure. Theoretical beta-particle spectra can also be derived by assuming that a number of unobserved beta transitions populate higher nuclear levels than postulated from gamma-ray measurements. Finally, Brady and England (1989) have evaluated delayed-neutron decay data, and supplemented their findings with model spectra to achieve the desired completeness: continuum spectra were derived, along with P_n and $\bar{v}$. These theoretical assessments generate estimated decay data that need to be supported and ultimately replaced with discrete measurements. Such requirements offer significant challenges that are in the process of being addressed through the implementation of experimental work using a wide range of facilities and powerful techniques (see Section 4.2, below).

Table 8
Actinide decay data — status, 1986; comments, 2000

Radionuclide	Data type[a]	Accuracy achieved by 1986 (%)[b]	Comments
^{228}Th decay chain	$t_{1/2}$	0.1–0.9	Overall, desired data accuracy has been achieved
	P_γ[c]	2–5	
^{229}Th decay chain	$t_{1/2}$	2	Possible need for marginal improvements
	P_γ[c]	1–3	
^{230}Th	$t_{1/2}$	0.4	Desired accuracy has been achieved
^{232}Th decay chain	$t_{1/2}$	0.4	No known stringent requirements; however, data need to be re-assessed (^{232}Th/^{233}U nuclear fuel cycle)
	P_γ	—	
^{233}Th	$t_{1/2}$	0.5	P_β and P_γ requirements are not satisfied
	P_β	~10	
	P_γ	~10	
^{231}Pa	$t_{1/2}$	0.3	Possible need for marginal improvements in P_α and P_γ
	P_α	2–7	
	P_γ	2–5	
^{233}Pa	$t_{1/2}$	0.4	Requirements for more accurate P_β data
	P_β	~10	
	P_γ	1	
^{232}U	$t_{1/2}$	0.7	Desired data accuracy has been achieved
	P_α	1	
	P_γ	1–2	
^{233}U	$t_{1/2}$	0.1	Data need to be re-assessed (^{232}Th/^{233}U nuclear fuel cycle)
	$(t_{1/2})_{sf}$	—	
	P_α	1–2	
	P_X[d]	—	
	P_γ	1–2	
^{234}U	$t_{1/2}$	0.1	Desired accuracy has been achieved
	$(t_{1/2})_{sf}$	~50	
	P_α	0.03–1	
	P_γ	1–2	
^{235}U	$t_{1/2}$	0.1	Requirement for more accurate P_α and P_γ data (particularly low-energy gamma rays (<120 keV))
	$(t_{1/2})_{sf}$	~50	
	P_α	5–12	
	P_γ	1	
^{236}U	$t_{1/2}$	0.1	Requirements for more accurate P_α and P_γ data
	$(t_{1/2})_{sf}$	3	
	P_α	5–15	
	P_γ	10	
^{237}U	P_γ	2–3	Requirements for more accurate P_γ data for the main gamma-ray transitions
^{238}U	$t_{1/2}$	0.1	P_α measurements have improved accuracy to 2%, so that a well-defined decay scheme can be constructed
	$(t_{1/2})_{sf}$	1.2	
	P_α	5–20	
	P_X[d]	—	
	P_γ	13	
^{239}U	$t_{1/2}$	0.2	Possible need for better defined P_β data (decay-heat calculations)
	P_β	2–20	
	P_γ	2	
^{236}Np	$t_{1/2}$	10	Requirements for more accurate $t_{1/2}$ and P_β data
	Branching fraction	2	
	P_β	?	
	P_γ	2	
^{236m}Np	$t_{1/2}$	2	Desired accuracy has been achieved
	Branching fraction	2	

Table 8 (*continued*)

Radionuclide	Data type[a]	Accuracy achieved by 1986 (%)[b]	Comments
^{237}Np	$t_{1/2}$	0.5	Significant efforts have been expended to measure P_α, P_γ, P_X and P_e (i.e., electron spectra); however, a consistent and comprehensive decay scheme has yet to evolve due to the underlying complexity
	P_α	20	
	P_X[d]	—	
	P_γ	1–2	
^{238}Np	$t_{1/2}$	0.1	Requirements for more accurate P_γ
	P_γ	5	
^{239}Np	$t_{1/2}$	0.2	Possible need for better defined P_β data (decay-heat calculations)
	P_β	2–15	
	P_γ	1–2	
^{236}Pu	$t_{1/2}$	3	Requirements for more accurate P_α and P_γ data
	P_α	1–3	
	P_γ	30	
^{237}Pu	$t_{1/2}$	0.1	Desired data accuracy would appear to have been achieved
	P_X[d]	—	
^{238}Pu	$t_{1/2}$	0.3	Desired data accuracy has been achieved
	$(t_{1/2})_{sf}$	4	
	P_α	<1	
	P_X[d]	2–3	
	P_γ	1–2	
^{239}Pu	$t_{1/2}$	0.1	Desired data accuracy has been achieved, with the derivation of a complex and comprehensive decay scheme
	P_α	1–2	
	P_X[d]	3	
	P_γ	<1	
^{240}Pu	$t_{1/2}$	0.1	Possible need for marginal improvements in P_α and P_γ
	$(t_{1/2})_{sf}$	3	
	P_α	1–2	
	P_X[d]	3	
	P_γ	1–2	
^{241}Pu	$t_{1/2}$	0.7	Concerns associated with $t_{1/2}$ have been assuaged; desired data accuracy has been achieved
	$(t_{1/2})_{sf}$	0.8	
	P_γ	1–2	
^{242}Pu	$t_{1/2}$	0.3	Requirements for better characterised P_X; other parameters are reasonably well defined
	$(t_{1/2})_{sf}$	1.5	
	P_α	<1	
	P_X[d]	—	
	P_γ	2–5	
^{241}Am	$t_{1/2}$	0.15	Requirements for improved accuracy in P_X and P_γ data; significant efforts have been made to determine P_γ (59.54 keV)
	P_α	1–2	
	P_γ	1–10	
	P_X[d]	3	
^{242}Am	$t_{1/2}$	0.1	Desired data accuracy has been achieved
	Branching fraction	1	
^{242m}Am	$t_{1/2}$	1.4	Requirements for improved accuracy in P_X; α decay mode has been well defined
	Branching fraction	0.03	
	P_X[d]	—	
^{243}Am	$t_{1/2}$	0.2	Both P_α and P_γ measurements are merited, and such studies have been made to improve the accuracy of those data
	P_α	0.5–20	
	P_X[d]	—	
	P_γ	2	
^{242}Cm	$t_{1/2}$	0.04	Desired data accuracy has been achieved
	$(t_{1/2})_{sf}$	2	
	P_γ	4–20	

Table 8 (*continued*)

Radionuclide	Data type[a]	Accuracy achieved by 1986 (%)[b]	Comments
^{243}Cm	$t_{1/2}$	0.3	While the major gamma-ray emissions are reasonably well characterised, some of the lower-intensity transitions are poorly defined
	P_α	1 – 3	
	P_X[d]	—	
	P_γ	2–10	
^{244}Cm	$t_{1/2}$	0.3	Desired data accuracy has been achieved
	$(t_{1/2})_{sf}$	0.4	
	P_α	<1	
	P_X[d]	3	
	P_γ	2–10	
^{245}Cm	$t_{1/2}$	1	Requirements for more accurate P_X and P_γ data
	P_α	0.5–2	
	P_X[d]	—	
	P_γ	10	
^{246}Cm	$t_{1/2}$	2	Requirements for more accurate $t_{1/2}$, P_X and P_γ data
	P_α	1–5	
	P_X[d]	—	
	P_γ	$\sim$10	
^{248}Cm	$t_{1/2}$	1	Requirements for more accurate P_X and P_γ data
	P_α	<1	
	P_X[d]	—	
	P_γ	$\sim$5	
^{250}Cf	$t_{1/2}$	0.7	Challenging requirements for $t_{1/2}$ and $(t_{1/2})_{sf}$ need to be addressed (0.2% and 2%, respectively)
	$(t_{1/2})_{sf}$	4	
^{252}Cf	$t_{1/2}$	0.3	Discrepant $t_{1/2}$ data
	$(t_{1/2})_{sf}$	0.3	

[a] $t_{1/2}$ — total half-life, $(t_{1/2})_{sf}$ — spontaneous fission half-life, P_α — alpha-particle emission probability, P_β — beta-particle emission probability, P_X — X-ray emission probability, P_γ — gamma-ray emission probability.

[b] Uncertainties for alpha-particle, beta-particle, gamma-ray and X-ray emission probabilities apply to the major transitions only, corresponding to the 1σ confidence level.

[c] Listed requirements for decay-chain radionuclides represent those for the more prominent transitions of all members of the decay chain.

[d] P_X refers to LX-ray emission probabilities.

The decay-data studies outlined above have generated considerable interest, and resulted in clear and definitive needs for improved measurements of specific parameters. Experimentalists have taken up this challenge in a number of ways to improve the quality of data, and so provided essential synergies between measurers, evaluators and theoreticians.

4. Decay-data measurements

A wide range of experimental techniques are used to quantify the decay parameters of radionuclides. While specific decay-data measurements are described below to give an indication of the focus of these on-going activities, they do not represent a comprehensive consideration of all such work and their resulting publications. Rather the author summarises the efforts made in recent years to resolve specific issues that have arisen as a consequence of applied and technical needs, or have been highlighted in the course of a series of extensive evaluations. Examples are given below, in which the author has been selective with the aim of highlighting a number of requirements that have been satisfied by accurate measurements.

National standards and other specialised laboratories undertake regular programmes of decay-data measurements. These studies are shaped by the demands of various applications (particularly within nuclear medicine), and the authoritative requirements generated by the relevant IAEA Co-ordinated Research Programmes described in Section 3. All of this work is carried out in order to recommend decay data of improved accuracy through a combination of reactor and accelerator irradiations, radiochemical purification, source preparation, and spectral measurement techniques. Considerable effort is also expended in closely related studies to develop our

understanding of the nuclear structure of the more complex nuclides.

4.1. Intermediate- and long-lived radionuclides

Problems arise in the characterisation of the decay parameters of intermediate- and long-lived radionuclides that can be readily addressed through a range of standard measurement techniques (such as alpha-particle and gamma-ray spectroscopy, and mass spectrometry). Various intermediate- and long-lived radionuclides (i.e., half-lives greater than a few minutes) are considered in this section, while short-lived nuclides with their particular measurement difficulties are assessed in Section 4.2.

4.1.1. Gamma-ray and alpha-particle energies

All gamma-ray energies should be adopted or derived from the recommended standards proposed by Helmer et al. (1979), and updated by Helmer and van der Leun (2000). Their extremely precise energy scale is based on a set of gamma-ray wavelength measurements made at the US National Institute of Standards and Technology, quoted in terms of optical wavelengths that define the meter. Recent improvements have resulted in the uncertainty of the wavelength-to-keV conversion factor being reduced from 2.6 to 0.3 ppm due to:

(i) revised lattice parameter for the Si crystals used in the wavelength measurements,
(ii) new set of adjusted fundamental constants,
(iii) new high-precision measurements.

Thus, the primary gamma-ray emission of ^{198}Au has a re-defined energy of 411.80205(17) keV. Helmer and van der Leun (2000) have generated a list of 260 gamma-ray energies for 50 radionuclides ranging from 24 to 4806 keV, and a subsidiary group of 70 additional lines that include 5 further radionuclides.

Alpha-particle energies are normally determined with respect to one or more accurately known standards, all traced back to absolute measurements on the magnetic spectrometer of the Bureau International des Poids et Mesures (BIPM). The design and operational characteristics of this spectrometer have been described by Grennberg and Rytz (1971), along with the source preparation procedures and the implementation of various correction factors. Thirty-one alpha-particle energies were determined with high accuracy, encompassing 20 radionuclides from ^{211}Bi to ^{253}Es. Modifications to the fundamental constants have an impact on the precise values of these primary alpha-particle energies, as noted by Rytz (1991); such adjusted data should be used to calibrate alpha-particle spectrometers.

4.1.2. Half-lives and emission probabilities

High-precision measurements of the gamma-ray emission probabilities of specific radionuclides are essential in their evolution as standards for detector calibration. A significant number of radiochemical laboratories are dedicated to these challenging studies, and have been involved in the development of various types of detector to measure decay parameters with improved accuracy. Such efforts are admirably demonstrated by the work of Miyahara et al. (1994, 1996, 1998, 2000), who have used $4\pi\beta$(ppc)$-\gamma$(HPGe) and $4\pi\beta$(pc)$-\gamma$(HPGe) coincidence techniques coupled to a two-dimensional data-acquisition system to measure the gamma-ray emission probabilities of various radionuclides (for example, ^{38}Cl, ^{75}Se, ^{166m}Ho, ^{182}Ta, ^{186,188}Re and ^{192}Ir). Uncertainties in the gamma-ray emission probabilities of ^{38}Cl were reduced from 4.8% to less than 1%, (as listed in Table 9), and these data have been used to calculate more accurate beta-particle branching fractions to the nuclear levels of ^{38}Ar (Miyahara et al., 1996).

Similar studies of other radionuclides have provided the impetus to re-evaluate some of the decay data recommended for the calibration of gamma-ray detectors. Thus, the emission probabilities of the ^{75}Se gamma rays have been determined (Miyahara et al., 1994) to be in good agreement with the recommended data from the IAEA-CRP evaluation (IAEA, 1991), and will be consolidated within the new IAEA Co-ordinated Research Programme (see Table 10).

Equivalent studies of the photon emission probabilities of ^{186}Re demonstrated the improvements made in the measurement of such data (Schönfeld et al., 1994; Miyahara et al., 2000; Woods, D.H. et al., 2000). Various $4\pi\beta-\gamma$ coincidence systems have been used to measure sets of highly consistent data (Table 11). Earlier measurements need to be evaluated in conjunction with these more recent data in order to produce a single set of recommended gamma-ray emission probabilities.

Two NaI(Tl) scintillation counters have been used to monitor KX-γ coincidences at small solid angles in order to determine the photon emission probabilities of ^{51}Cr and ^{88}Y (Konstantinov et al., 1994). This counting technique generates accurate data for EC-decaying nuclides with no conversion-electron emissions:

^{51}Cr $\quad P_{\gamma}^{\mathrm{abs}}(320\,\mathrm{keV}) = 0.0996(9); P_{\mathrm{XK}} = 0.232(3)$

^{88}Y $\quad P_{\mathrm{XK}} = 0.615(6).$

The same workers have standardised and determined the half-life of ^{55}Fe by measuring the 5.9 keV KX-ray with a pressurised 4π proportional counter (Karmalitsyn et al., 1998). Thin high-quality sources were prepared, and monitored periodically over 8 yr to give a half-life of 995(3) d, in good agreement with earlier studies and an IAEA-CRP evaluation (IAEA, 1991).

Table 9
Gamma-ray emission probabilities of ^{38}Cl (Miyahara et al., 1996)

E_γ (keV)	Absolute emission probability (P_γ^{abs})
1642.7	0.3338(32)
2167.7	0.4477(31)

Table 10
Gamma-ray emission probabilities of ^{75}Se

E_γ (keV)	Absolute emission probability (P_γ^{abs})	
	Miyahara et al. (1994)	IAEA-CRP (IAEA, 1991)
96.7	0.03392(20)	0.0341(4)
121.1	0.17468(62)	0.171(1)
136.0	0.5883(20)	0.588(3)
198.6	0.01500(9)	0.0149(1)
264.7	0.5870(17)	0.590(2)
279.5	0.25112(73)	0.250(1)
303.9	0.01314(8)	0.0131(1)
400.7	0.11337(40)	0.115(1)

The calibration of gamma-ray detectors at high energies (>2 MeV) has proved to be problematic. Emission probability data above 2 MeV are uneven in quality, and historically efficiency curves have been extrapolated linearly from the more reliable data of lower-energy transitions (i.e., linear extrapolation of log(efficiency) vs. log(E_γ)). This approach has been shown to be a serious oversimplification, and a correction factor has to be introduced for $E_\gamma > 2$ MeV (representing 30% variation at 5 MeV). Efforts have focused on the construction of efficiency curves through the measurement of the gamma-ray emission probabilities of ^{56}Co, which covers the energy range from 0.847 to 3.548 MeV (Hautala et al., 1978; Stewart and Shaban, 1980; Bradley et al., 1986; Wang et al., 1988). Extensive studies have also been undertaken to characterise the high-energy gamma rays emitted by ^{66}Ga from 0.70 to 4.81 MeV (Phelps et al., 1970; Camp and Meredith, 1971; Endt and Alderliesten, 1994; IAEA, 1991). Similarly, prompt gamma-ray emissions from specific nuclear reactions can be adopted as secondary calibrants, and particular emphasis has been placed on the following:

^{14}N(n, γ)^{15}N* with reasonably well-characterised emissions from 1.68 to 10.83 MeV, and ^{35}Cl(n, γ) ^{36}Cl* with appropriate emissions from 0.52 to 8.58 MeV.

Improved high-energy gamma-ray data are in the process of being determined for these suitable radionuclides and nuclear reactions, driven by the requirements for neutron activation analysis. Other candidates include ^{11}B(p, γ)^{12}C*, ^{12}C(p, p′γ)^{12}C*, ^{45}Sc(p, γ)^{46}Ti* and similar proton-capture reactions that emit gamma-ray cascades with high energies (IAEA, 1991).

Table 11
Gamma-ray emission probabilities of ^{186}Re

E_γ (keV)	Absolute Emission Probability (P_γ^{abs})		
	Schönfeld et al. (1994)	Miyahara et al. (2000)	Woods, D.H. et al. (2000)
122.61	0.00603(6)	0.00604(3)	0.00597(8)
137.16	0.0939(9)	0.0949(3)	0.0935(10)
630.33	0.000293(6)	—	0.000295(6)
767.47	0.000327(6)	—	0.000350(9)

Although ^{67}Ga has found application in the field of nuclear medicine, the decay scheme involves an ill-defined electron-capture branch directly to the ground state of ^{67}Zn. The uncertainty in this EC branch impacts significantly on other parameters in the decay scheme. Therefore, a new measurement was undertaken to give an EC branch of 0.0401(27) to the ground state (Simpson and Ntsoane, 2000). Solutions of ^{67}Ga were standardised by 4π(LS)e,X–γ coincidence, using a NaI(Tl) detector to monitor the gamma rays. The emission probability of the internal conversion electrons from the 93.3 keV gamma-ray transition was determined to be 0.325(1) from these studies and the measurements of Attie et al. (1998), leading to the proposed EC branch to the ground state.

The half-lives of some long-lived radionuclides are important in assessing procedures for the decommissioning of reactor facilities and the storage of irradiated fuel. Significant nuclides in this category include ^{79}Se, ^{108m}Ag and ^{126}Sn, and some progress has been made in determining their decay data. For many years, the half-life of ^{108m}Ag was assumed to be 127(7) yr, but a recent measurement at PTB Braunschweig has produced a significantly different value of 418(15) yr (Schötzig et al., 1992); this higher value is judged to be of improved quality, and has been adopted in a number of recent evaluations. Both ^{79}Se and ^{126}Sn are extremely long-lived ($>10^4$ yr), and their half-lives are best measured by means of mass spectrometric techniques. This accurate method of analysis has been used for ^{126}Sn to give a recommended half-life of $2.345(71)\times10^5$ yr (Haas et al., 1996; Oberli et al., 1999), in good agreement with a radiochemical measurement of $2.5(2)\times10^5$ yr (Zhang Shengdong et al., 1996). A series of radiochemical measurements have been made on ^{79}Se to determine a half-life of $4.8(4)\times10^5$ yr (Yu Runlan et al., 1995) and $1.13(17)\times10^6$ yr (Li Chunsheng et al., 1997). The same authors have also carried out activity and accelerator mass spectrometric studies to give a value of $1.1(2)\times10^6$ yr (Jiang Songsheng et al., 1997). Further

mass spectrometric measurements are merited to address the existing uncertainty in this parameter, and confirm the validity of the most recent study.

^{125}Sb has been judged to be an appropriate radionuclide for the calibration of gamma-ray detectors. As a consequence, $\gamma-\gamma$ angular correlation measurements have been made to determine the multipolarities and mixing ratios of a number of important gamma-ray transitions (Roteta and Garcia-Torano, 1998). A conventional combination of detectors was used to derive the directional correlation factors of the 321.03–176.33, 204.14–176.33 and 116.95–204.14 keV cascades and the mixing ratios of the individual transitions. The beta branch of ^{125}Sb to the long-lived isomeric state of ^{125m}Te is also important in determining the decay scheme; this parameter has been measured to be 0.243(3), compared with a value of 0.231(10) derived from an earlier study (Grau Carles et al., 1998).

Total absorption gamma-ray spectrometry (TAGS) has been used with remarkable success to measure the summed gamma-ray spectra for several fission products with half-lives between 5 seconds and a few hours (Helmer et al., 1994a,b; Greenwood et al., 1996, 1997). These spectra were collected in the singles mode by a 25.4 cm diameter by 30.5 cm long NaI(Tl) well-detector, and in coincidence with a Si beta-particle detector mounted in the well. If there are no losses (via photon escape, attenuation or internal conversion) and no interference from any beta particles (electrons and their bremsstrahlung), each event in the NaI(Tl) detector gives the summed gamma energy and the energy of the level populated in that specific beta decay. The deduced P_β- distributions can be converted to β strength distributions, and provide tests of the completeness of any proposed decay scheme. Thus, a particular decay scheme can be postulated to calculate a simulated TAGS spectrum, and the resulting data compared with the measured singles spectrum (Fig. 4 for ^{141}Cs). The decay scheme of ^{141}Cs involves at least 72 excited levels of ^{141}Ba, and the half-life of 25 s makes a study of this radionuclide difficult. Fig. 4 reveals that the P_β- for the low-energy levels of the simulation are too high while most of the higher levels are too low. Therefore, several new levels were introduced over the energy range from 2525 to 4950 keV: total beta feeding in the region 100–1500 keV was reduced by a factor of 2.2, and increased by a factor of 3.4 between 2000 and 4000 keV to give the improved fit shown in Fig. 5. This method of study and analysis is an extremely powerful technique, and should be applied to solve similar decay-scheme difficulties with other radionuclides.

^{133}Ba and ^{133}Xe undergo electron-capture and beta decay, respectively, to populate equivalent nuclear levels of ^{133}Cs (Fig. 6). The relatively long half-life and low-energy gamma rays of ^{133}Ba make this radionuclide suitable for the calibration of Si(Li) and HPGe detectors. An extensive measurement programme was organised under the auspices of the International Committee for Radionuclide Metrology (ICRM), and the resulting data were reported

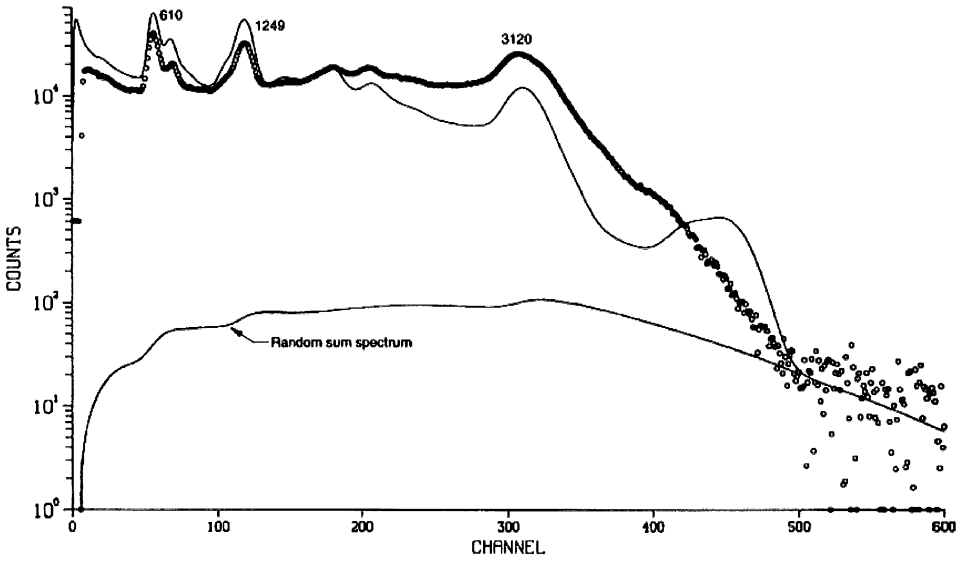

Fig. 4. Comparison of a measured singles spectrum for ^{141}Cs with a simulated spectrum based on previously proposed decay scheme (decay energy of 5256 keV) — Helmer et al. (1994b). [Reprinted by permission of Elsevier Science BV from 'Methodology for the measurement of β^--decay intensity distributions from the analysis of total absorption γ-ray spectra' by Helmer, R.G., Putnam, M.H., Greenwood, R.C., Willmes, H., Nucl. Instr. Meth., **A351**, 406–422. Copyright 1994 by Elsevier Science BV, Molenwerf 1, PO Box 211, 1000 AE Amsterdam, The Netherlands].

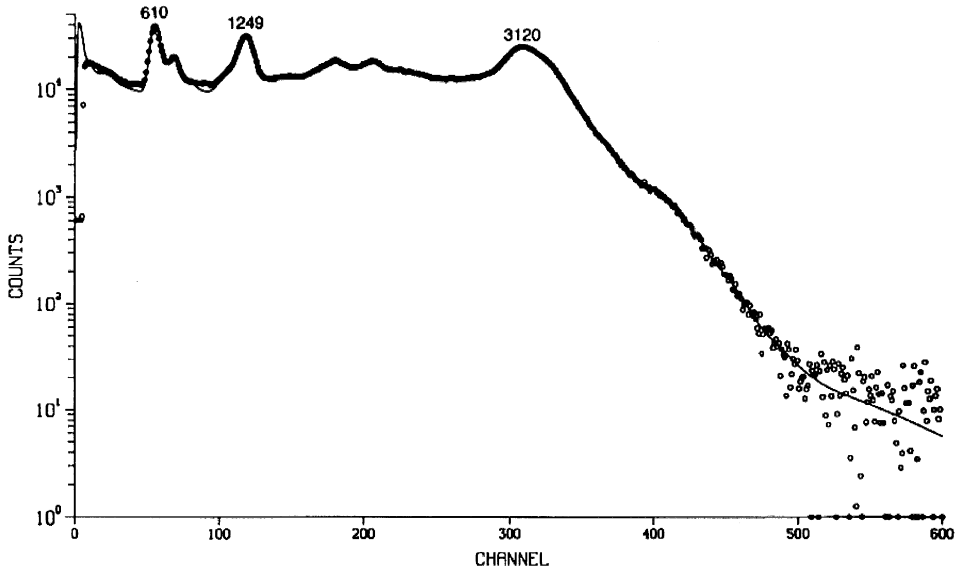

Fig. 5. Comparison of a measured singles spectrum for ^{141}Cs with a simulated spectrum in which new $P_\beta(E)$ values have been introduced after adding further nuclear levels — Helmer et al. (1994b). [Reprinted by permission of Elsevier Science BV from 'Methodology for the measurement of β^--decay intensity distributions from the analysis of total absorption γ-ray spectra' by Helmer, R.G., Putnam, M.H., Greenwood, R.C., Willmes, H., Nucl. Instr. Meth., **A351**, 406–422. Copyright 1994 by Elsevier Science BV, Molenwerf 1, PO Box 211, 1000 AE Amsterdam, The Netherlands].

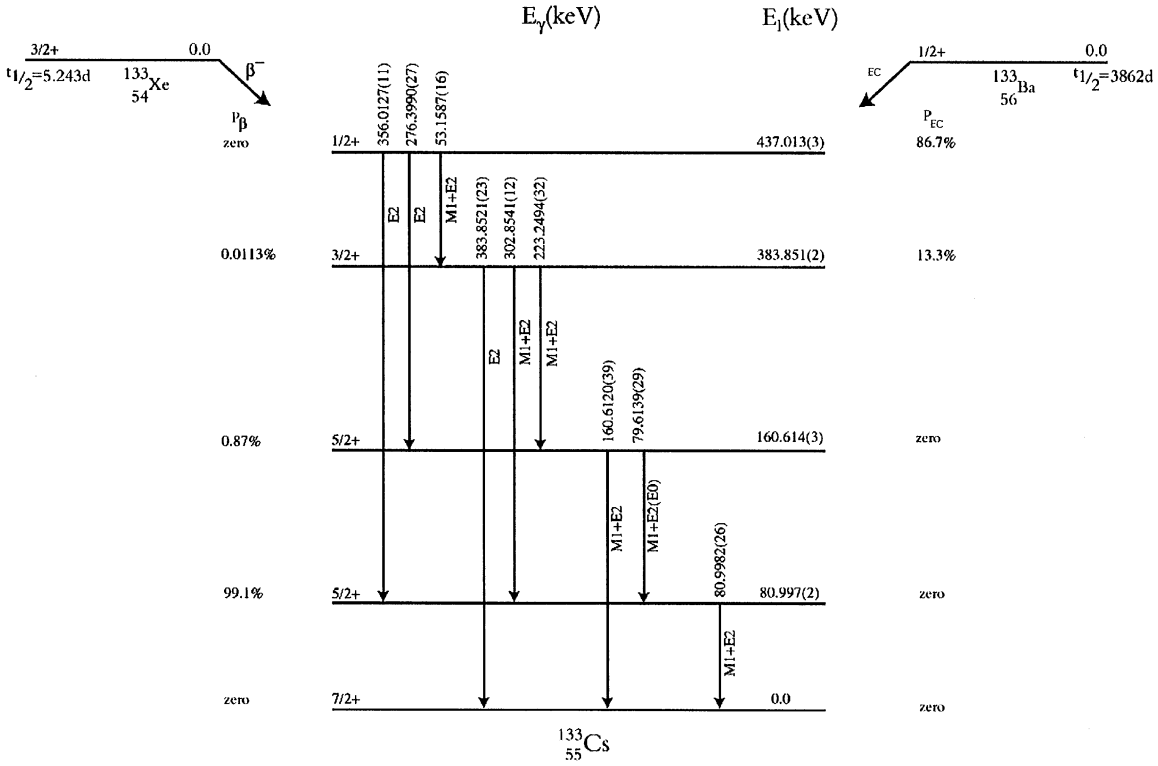

Fig. 6. Decay schemes of ^{133}Xe and ^{133}Ba.

during the course of an IAEA-CRP (Chauvenet et al., 1983; IAEA, 1991). The 81 keV gamma ray is particularly important, although uncertainties remain in defining the absolute emission probability of this transition. Further studies are merited to resolve the uncertainty, starting with an in-depth evaluation of all relevant measurements.

^{153}Sm has been used in the treatment of prostate cancer, and there is a need to quantify the various decay parameters of this radionuclide with greater accuracy. A $4\pi(pc)-\gamma$ coincidence system has been used to measure the half-life (Bowles et al., 1998), with the NaI detector gated on the 103 keV photopeak. Various sources were monitored over five half-lives to determine a mean half-life of 46.285(4) h; gamma-ray emission probabilities were also measured by means of a HPGe detector, including P_γ (103 keV) of 0.285(5). These data differ from the equivalent studies of Coursey et al. (1987), which implies a continuing requirement to determine the decay scheme of this radionuclide with greater confidence.

Both ^{152}Eu and ^{155}Eu have been categorised as suitable to develop as secondary and primary standards, respectively, for the calibration of gamma-ray detectors. Good quality decay data are also required to characterise ^{154}Eu for environmental monitoring and waste management applications. Efforts continue to improve the accuracy of the decay data for these radionuclides. Over more than 20 yr, workers at PTB Braunschweig have measured the activities of ^{152}Eu, ^{154}Eu and ^{155}Eu sources by means of a pressurised $4\pi\gamma$ ionisation chamber and Si and Ge semiconductor detectors (Siegert et al., 1998). Subsets of the resulting data have been analysed to give the following half-lives

^{152}Eu : 4936.6(20) d by ionisation chamber,

^{154}Eu : 3146(11) d by Ge detector,
3138.1(16) d by ionisation chamber,

^{155}Eu : 1739(8) d by Ge detector.

A number of different measurements have been made of the gamma-ray emission probabilities for ^{154}Eu (Hammed et al., 1992; Smith et al., 1992); both sets of data demonstrate that this radionuclide is well-characterised. A similar study has been made of the X- and gamma-ray emission probabilities of ^{155}Eu (Egorov and Chechev, 1994) using a combination of a $4\pi\beta-\gamma$ coincidence system (to measure the specific activity) and Ge-planar detector (for absolute and relative emission probabilities).

An extensive series of measurements have been made to determine the X- and gamma-ray emission probabilities of ^{169}Yb decay under the auspices of EUROMET, action 410 (Morel et al., 2000). Point sources were made available, and eleven independent laboratories generated one or more sets of data each, including activity measurements and photon emission rates. A majority of the participants used coaxial HPGe and Ge(Li) detectors to determine the photon emission rates and emission probabilities, and these data were used by the co-ordinators of the programme to recommend mean values. A simplified decay scheme is shown in Fig. 7, and the data derived in this EUROMET exercise are listed in Table 12. The emission probabilities had reduced uncertainties of 1 to 2% for the LX-rays, 1% for the KX-rays, and $\leqslant 0.5\%$ for the gamma rays. Further details have been published by some of the participating laboratories (Sazonova et al., 2000; Razdolescu et al., 2000).

Naturally-occurring ^{226}Ra is an important radionuclide that is often used to calibrate detectors up to an energy of 3.2 MeV, and plays a significant role in the monitoring of environmental radioactivity. There are a number of discrepancies in the recommended decay data for this nuclide and daughter products, of which the emission probability of the 186.21 keV gamma ray is most noteworthy. While the relative emission probability of this gamma ray has been reasonably well defined with respect to the 609 keV transition of ^{214}Bi, the determination of an accurate and credible absolute emission probability has proved to be problematic. Recent measurements are listed in Table 13. While those direct studies indicate a value of 0.0353(3), a number of decay-scheme evaluations recommend 0.0328(3) in order to maintain a population/depopulation balance of the 186.21 keV nuclear level of ^{222}Rn. This discrepancy of 7% between the measurements and decay-scheme balance represents an unsatisfactory situation that needs to be resolved. The measured absolute emission probabilities are in good agreement, and their weighted mean value should be adopted. Under these circumstances, two possible explanations should be explored that could address the resulting inconsistency:

(i) anomalous internal conversion coefficients for the E2 transition (judged to be unlikely);
(ii) poorly defined alpha-particle emission probabilities to the ground and 186.21 keV nuclear levels of ^{222}Rn.

There is increased interest in the use of thorium fuel in new reactor designs, and hence there is a need for improved accuracy in such nuclear data as the decay schemes of ^{233}Th and ^{233}Pa. Therefore, studies have been undertaken to determine the half-lives of both of these radionuclides: samples of thorium were irradiated in a research reactor, and either placed immediately in front of a Ge(Li) detector to monitor ^{233}Th (Usman et al., 1998), or a HPGe detector two days after irradiation to follow ^{233}Pa decay (Usman and MacMahon, 2000). Repeat irradiations and measurements were

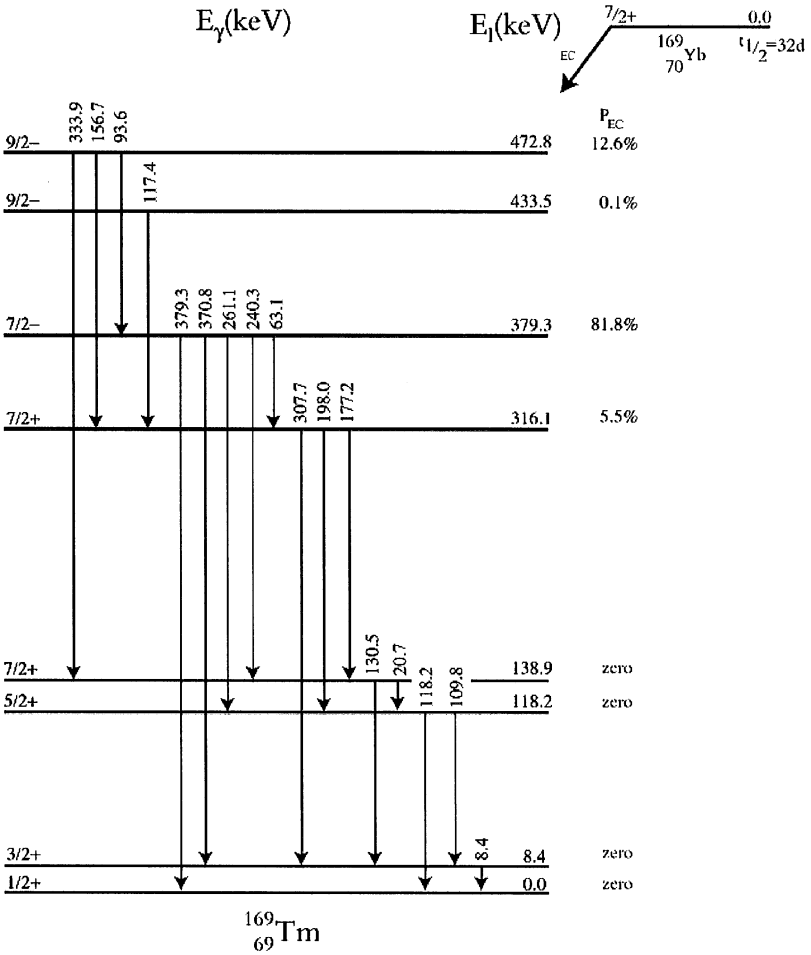

Fig. 7. Simplified decay scheme of ^{169}Yb.

carried out, and various statistical analyses were applied to all of the half-life data (Rajput and MacMahon, 1992) to give recommended half-lives of 21.83(4) min for ^{233}Th, and 26.975(13) d for ^{233}Pa.

Environmental monitoring of ^{238}U (through ^{234}Th/^{234m}Pa) has relied on an abundance of 0.0059 for the 1001 keV gamma ray of ^{234m}Pa as reported by Bjørnholm and Nielsen (1963), while others have used a value of 0.0091 as recommended by Sutton et al. (1993). Attempts to quantify ^{234}Th by gamma-ray emission measurements may be compromised by either the adoption of an incorrect abundance for the 63.3 keV gamma ray or undercorrection of the self-absorption of this relatively low-energy emission by the sample (or a combination of both). Comprehensive evaluations have been undertaken of the available decay data for ^{234m}Pa and ^{234}Th (Duchemin et al., 1994; Adsley et al., 1998), in order to produce recommended decay data that will provide a credible basis on which to determine and report on the environmental monitoring of ^{234m}Pa and ^{238}U. Gunnink and Tinney (1971) produced the first published evidence that the absolute emission probability of the 1001 keV gamma-ray transition of ^{234m}Pa was significantly higher than previously thought, with a value of 0.00828 (and 1% uncertainty). An additional systematic uncertainty of 2% can be identified with previous measurements by Gunnink and co-workers to give an absolute value of 0.00828(25) for the 1001 keV gamma-ray emission probability. Further gamma-ray studies in the 1980s provided substantial evidence for the validity of these data (Momeni, 1982; Moss, 1986; Scott and Marlow, 1990; Siemon et al., 1992; Lin and Harbottle, 1992; Jagam and Simpson, 1992). An extensive data evaluation generated a normalisation factor of 0.00835(11) for the gamma-ray emission probabilities (i.e., P_{γ}^{abs} (1001 keV) of 0.00835(11)), as described by Adsley et al. (1998). A comprehensive evaluation has also been undertaken to produce

Table 12
Gamma-ray emission probabilities of ^{169}Yb (Morel et al., 2000)

E_γ (keV)	Absolute emission probability (P_γ^{abs})
8.4	0.00347(17)[a]
20.7	0.001958(25)
63.1	0.4387(23)
93.6	0.02587(13)
109.8	0.1741(7)
117.4	0.000431(18)
118.2	0.01874(10)
130.5	0.1146(4)
156.7	0.000103(11)
177.2	0.2241(7)
198.0	0.3612(11)
240.3	0.001144(42)
261.1	0.01697(11)
307.7	0.1013(3)
333.9	0.0000160(11)
370.8	<0.00002
379.3	0.0000062(11)

[a] Deduced from proposed decay scheme (and other data).

Table 13
Absolute emission probability of 186.21 keV gamma ray of ^{226}Ra

Reference	P_γ^{abs}(186.21 keV)
Olson (1983)	0.03650(5)
Schötzig and Debertin (1983)	0.0351(6)
Lin and Harbottle (1991)	0.0359(6)

recommended decay data for ^{234}Th on the basis of the following:

Godart and Gizon (1973) 0.033(3),
Momeni (1982) 0.0405(20),
Scott and Marlow (1990) 0.036(1),

for the absolute emission probability of the 63.30 keV gamma ray; a weighted mean value of 0.037(2) was derived. This combination of improved decay data has resulted in good agreement between ^{234}Th and ^{234m}Pa activities in secular equilibrium.

An extensive study has been made of the electron-capture decay of ^{231}U prepared by proton irradiation of ^{233}U via the ^{233}U(p, 3n)^{231}Np reaction and ^{231}Np decay (Browne et al., 1994). Gamma-ray singles and $\gamma-\gamma$ coincidence spectra were measured in the same experiment by means of two high-purity Ge detectors. Conversion electrons for the 58.5 and 84.2 keV transitions were detected by a Hamamatsu S2620 PIN detector operated in conjunction with a high-purity Ge detector. These comprehensive studies confirmed the known nuclear level scheme of ^{231}Pa, and revealed that the relative KX-ray emission probabilities can be used directly to normalise the resulting decay scheme. Thus, a more precise set of decay data have been measured to improve considerably the ^{231}U decay scheme.

Koua Aka et al. (1996) have studied the gamma-ray emissions associated with the α-decay of ^{233}U. A complex singles spectrum was observed with a high-purity Ge detector, and $\gamma-\gamma$ coincidence measurements were also made with three high-purity Ge detectors. The energies and intensities of 178 gamma rays were determined of which 49 were reported for the first time. An extremely complex decay scheme was derived for ^{233}U in which the authors focused on the high-energy states of ^{229}Th fed by the alpha-particle decay of ^{233}U.

Naturally-occurring ^{235}U has a half-life of $7.038(5)\times10^8$ yr, and is the primary fuel for nuclear power generation. A reasonably complete and complex decay scheme can be derived from the alpha-particle studies of Vanó et al. (1975), and the gamma-ray measurements of Teoh et al. (1974), Vanó et al. (1975), Baranov et al. (1977), Vaninbroukx and Denecke (1982), Banham and Jones (1983), Olson (1983), Helmer and Reich (1984), and Lin and Harbottle (1992). There are variations in the measured energy range and quality of the gamma-ray data, particularly the relative emission probabilities of the low-energy gamma rays. Despite these difficulties, there is good agreement between measurements to determine the normalisation factor of the gamma-ray emissions. The alpha-particle data are judged to be inadequate, and further measurements are merited to quantify these emission probabilities with greater confidence. Similarly, greater emphasis also needs to be placed on determining the emission probabilities of the lower-energy gamma rays (<120 keV). Improved data measurements of this type would contribute significantly to the derivation of a fully consistent decay scheme for ^{235}U.

Improved measurements of alpha-particle emission probabilities can impact greatly on decay-scheme studies, as demonstrated in the determination of the alpha decay of ^{238}U by Garcia-Torano (2000). While gridded ionisation chambers have been used in the past to measure P_α values, this recent measurement is believed to be the first study to use semiconductor detectors. Various types of silicon-implanted systems were used to generate the emission probabilities listed in Table 14. These data are sufficiently accurate to permit a simple and well-defined decay scheme to be derived with relative ease.

Significant efforts have been made to resolve a number of major inconsistencies in the decay data of ^{237}Np (Vaninbroukx et al., 1984; Woods et al., 1988; Lowles et al., 1990; Pearcey et al., 1990; Bortels et al., 1990; Sibbens and Denecke, 2000; Woods, S.A. et al., 2000; Luca et al., 2000). However, despite precise

Table 14
Alpha-particle emission probabilities of ^{238}U (Garcia-Torano, 2000)

E_α (keV)	Absolute emission probability (P_α)
4038 (3)	0.0013 (3)
4150 (3)	0.2233 (50)
4198 (3)	0.7754 (50)

measurements of alpha-particle, gamma-ray and conversion-electron emission probabilities, difficulties continue to be encountered in reconciling these data and producing a comprehensive and consistent decay scheme. Various forms of high-purity Ge detector have been used to determine gamma-ray emission probabilities from as low as 5.18 and 8.03 keV to 279.65 keV (Vaninbroukx et al., 1984; Lowles et al., 1990; Luca et al., 2000; Schötzig et al., 2000; Woods, S.A. et al., 2000). A $\pi/2$ double-focusing beta spectrometer was modified to measure conversion-electron emission probabilities (Woods et al., 1988; Pearcey et al., 1990), and high-resolution planar silicon detectors resolved the extremely complex alpha-particle spectrum of ^{237}Np (Bortels et al., 1990; Sibbens and Denecke, 2000), as shown in Fig. 8. Low-energy gamma rays in the decay scheme pose significant analytical problems, with interference by X-rays (from detector components and daughter radionuclides) and escape peaks, and the need to determine conversion-electron emission probabilities. The main features of the proposed decay scheme are shown in Fig. 9, including a number of postulated low-energy gamma-rays. Inconsistencies between the conversion-electron and gamma-ray data need to be resolved, and the resulting recommendations need to exhibit consistency with the accurate alpha-particle emission probabilities.

Bland et al. (1992) used a planar intrinsic Ge detector to measure the low-energy gamma rays (10–60 keV) and LX-rays emitted by ^{239}Pu and ^{241}Am, while Lépy and Debertin (1994) undertook studies of the LX-rays of ^{239}Pu and ^{240}Pu with a Si(Li) detector. Improvements in data accuracy were achieved for the large number of X-rays because of the spectral fitting procedure and the correct identification of the Compton scattering and escape peaks. Lépy and Debertin used high-purity ^{239}Pu sources to resolve the individual peaks within the various LX-ray subgroups; equivalent data for ^{240}Pu were less accurately quantified.

The complex decay scheme of ^{241}Am contains significant numbers of low-intensity gamma-ray transitions that are believed to depopulate over 40 nuclear levels of ^{237}Np above 200 keV (Genoux-Lubain and Ardisson, 1978a,b; Abdul-Hadi, 1998). Efforts have focused on the characterisation of specific low-energy gamma rays emitted by this radionuclide, particularly the 59.5 keV emission that could be adopted for detector calibration (Denecke, 1987). Alpha-particle measurements represent important adjuncts to the gamma-ray studies, and furnish supportive data that can assist in the resolution of imbalances associated with the population/depopulation of the nuclear levels of ^{237}Np below 160 keV (Bland, 1994). Such combinations of accurately measured decay data are an extremely powerful tool in the formulation of credible decay schemes and well-defined data sets. An absolute emission probability of 0.360(1) can be derived for P_γ (59.5 keV) by a weighted-mean analysis, although further assessments are merited to derive a comprehensive decay scheme.

A similar combination of alpha-particle and gamma-ray studies has proved beneficial in determining the decay scheme of ^{243}Am, as well as ^{239}Np and ^{239}U (Garcia-Torano et al., 1992; Woods et al., 1996; Sardari et al., 1996). Alpha-particle emission probabilities were measured with improved accuracy by two teams of

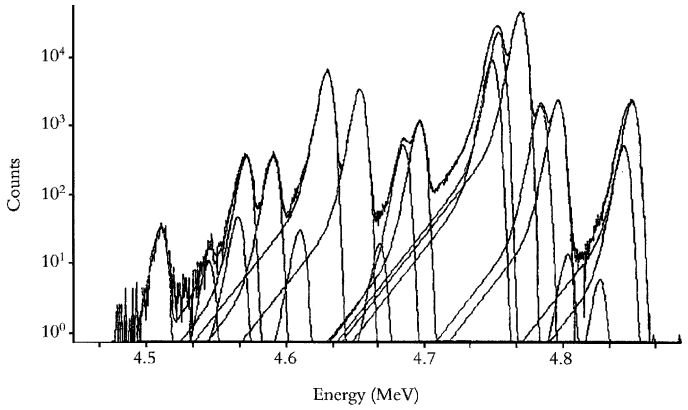

Fig. 8. ^{237}Np alpha spectrum with 20 α-particle peaks fitted — Sibbens and Denecke (2000). [Reprinted by permission of Elsevier Science Ltd. from 'Determination of the absolute alpha-particle emission probabilities of ^{237}Np' by Sibbens, G., Deneke, B., Appl. Radiat. Isot., **52**, 467–470. Copyright 2000 by Elsevier Science Ltd., PO Box 211, 1000 AE Amsterdam, The Netherlands].

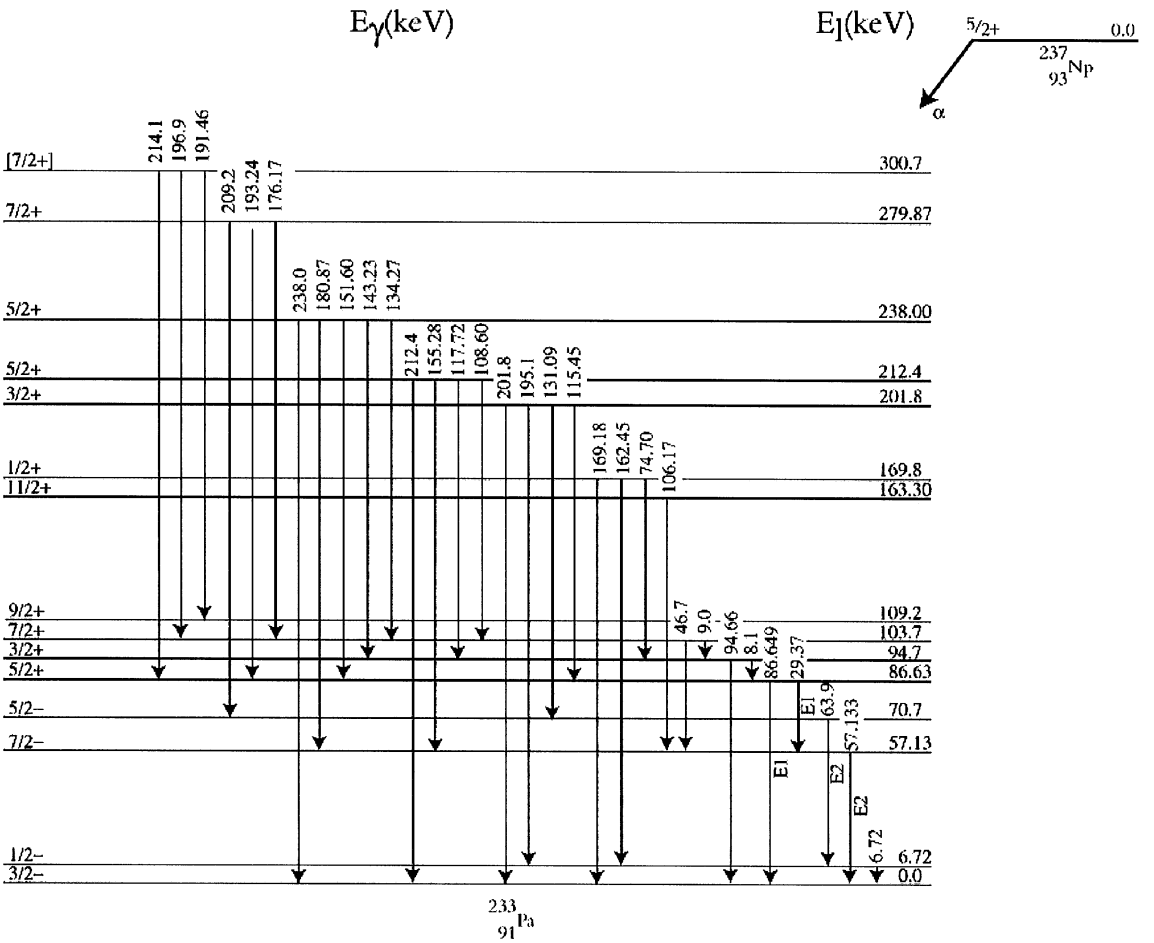

Fig. 9. Simplified decay scheme of ^{237}Np.

spectroscopists at CIEMAT and CBNM (now IRMM), as listed in Table 15. The most recently measured gamma-ray emission probabilities for ^{243}Am are compared in Table 16 (Woods et al., 1996; Sardari et al., 1996). These data are reasonably consistent, with the exception of the 142 keV transition. ^{239}U beta decay has also been assessed in one of these studies (Sardari et al., 1996) to produce beta-particle emissions probabilities with improved accuracy that can be traced back to the precision of the alpha-particle data of ^{243}Am populating the same nuclear levels.

A number of alpha-particle emitters were studied a significant time ago, and new measurements of their alpha-particle emission probabilities are merited with improved detector systems. Thus, Garcia-Torano (1998) has used various forms of silicon detector to determine the α-decay parameters of ^{244}Cm for the first time in over 30 yr. The resulting data are in very good agreement with the earlier measurements using magnetic spectrometers, with the added bonus that the recommended alpha-particle emission probabilities can now be quoted to an improved accuracy.

Some uncertainties have existed in defining a consistent and comprehensive decay scheme for ^{245}Cm. These problems have been addressed by a study of alpha-particle feeding to the nuclear levels of daughter ^{241}Pu (Shannon et al., 1994). A combination of HPGe and LEPS (low-energy photon spectrometer) were adopted to enhance the detection of low-energy gamma rays for the $\gamma-\gamma$ studies, while HPGe and Si(Au) surface barrier detectors were used for $\alpha-\gamma$ measurements. Previously problematic 205 and 232 keV gamma rays were unambiguously placed within the level scheme, while other emissions were identified with contaminants or germanium escape peaks.

More than thirty α-particle emissions have been identified with the decay of ^{249}Cf to ^{245}Cm, although no gamma-ray emissions have been observed to de-excite many of the proposed nuclear levels above 442 keV. Therefore, Koua Aka et al. (1996) have

Table 15
Alpha-particle emission probabilities of ^{243}Am (Garcia-Torano et al., 1992)

E_α (keV)	Absolute emission probability (P_α)		
	CIEMAT	CBNM (IRMM)	Recommended
5006.3	0.000019	0.000014	0.000016(5)
5033.9	0.000035	0.000031	0.000033(5)
5086.0	0.000059	0.000052	0.000056(7)
5111.6	0.00011	0.000096	0.00010(1)
5178.1	0.0137	0.0135	0.0136(1)
5232.8	0.1146	0.1147	0.1146(3)
5275.1	0.8673	0.8675	0.8674(6)
5318.0	0.00193	0.00184	0.00190(7)
5348.6	0.00231	0.00230	0.00230(7)

Table 16
Gamma-ray emission probabilities of ^{243}Am

E_γ (keV)	Absolute emission probability (P_γ^{abs})	
	Woods et al., 1996	Sardari et al., 1996
43.53	0.0593(10)	0.0572(17)
74.67	0.667(12)	0.684(13)
86.79	0.00342(15)	0.00344(9)
142.18	0.00117(5)	0.001068(26)

undertaken a study of the γ-ray emissions by means of high-purity Ge detectors. All of the observed transitions were incorporated into the decay scheme that evolved from this study: 14 excited states are de-excited via 35 gamma-ray transitions, and alpha-particle emission probabilities were derived from these data. Further gamma-ray and alpha-particle measurements are merited to support the work of Koua Aka et al. (1996).

Decay-data studies are undertaken to gain a greater fundamental understanding of atomic and nuclear structure. The measurements considered above represent an extremely limited selection of the work carried out in recent years. Emphasis has been placed on those radionuclides possessing decay characteristics that may be appropriate as calibrants for the construction of accurate detector-efficiency curves, and for other important applications.

4.2. Short-lived radionuclides

The experimental study of short-lived, neutron-rich radionuclides poses particularly difficult problems of source preparation and retrieval of samples for rapid purification and analysis. "Short-lived" radionuclides in this review are loosely defined as having half-lives of the order of a few minutes and less. Many of these nuclides undergo β^- and β^-n decay to populate highly-excited nuclear levels of basic interest, and undergo decay processes of importance in calculations to determine specific facets of reactor design and operation (e.g., quantification of delayed-neutron emissions and decay-heat calculations). Theoretical models have been developed because of a lack of appropriate data (see Section 3), but these approximations need to be supported whenever possible by some form of discrete data obtained through measurement.

4.2.1. Total beta energy (Q_β)

Mean beta energies are important input in decay-heat calculations, and the frequent inability to derive these parameters directly from discrete decay data poses significant problems. Under these circumstances, the measurement of Q_β can provide an alternative route to obtain reasonably accurate predictions of the β^- component. A sound knowledge of Q_β also provides reliable information on atomic masses, nuclear forces and the behaviour of radionuclides far from the line of stability. Various methods have been used to generate neutron-rich fission products, before separating them rapidly by means of on-line mass separators and producing Fermi–Kurie plots of the beta spectra through $\beta-\gamma$ coincidence and β singles techniques (Stippler et al., 1978; Wünsch et al., 1978; Decker et al., 1980; Iafigliola et al., 1983; Przewloka et al., 1992a,b; Ikuta et al., 1994). Beta spectra in coincidence with individual gamma-ray emissions are used to determine the β^- endpoint energy (Fig. 10) as described by Rehfield (1978), and these data can be compared with theory to improve future predictions.

4.2.2. Delayed-neutron data

Delayed-neutron decay data are important input to the modelling of the nuclear fission process. These data can also provide insights into some of the more uncertain features of nuclear structure and the population of unbound levels of transient nuclei (Nuh, 1975; Nuh et al., 1977; Shalev and Rudstam, 1977). Linear accelerators and research reactors with high-neutron flux have been used to generate and monitor short-lived, delayed-neutron emitters, in conjunction with combinations of singles and coincidence counting equipment (e.g., n$-\gamma$, $\beta-\gamma$ and $\gamma-\gamma$). Extensive studies have been made of the neutron and gamma-ray data generated by neutron-rich bromine, rubidium, antimony, tellurium, iodine and caesium radionuclides to provide extensive level-density information and evidence of complex β^-n decay (Kratz et al., 1979; Ohm et al., 1980; Hoff, 1981; Kratz et al., 1982; Kratz et al., 1983; Raman et al., 1983; Greenwood and Caffrey, 1985; Greenwood and Watts, 1997).

The complexity of β^- and β^-n decay is amply demonstrated by the ^{87}Br–^{87}Kr–^{86}Kr studies of Raman et al. (1983). High-resolution neutron resonance

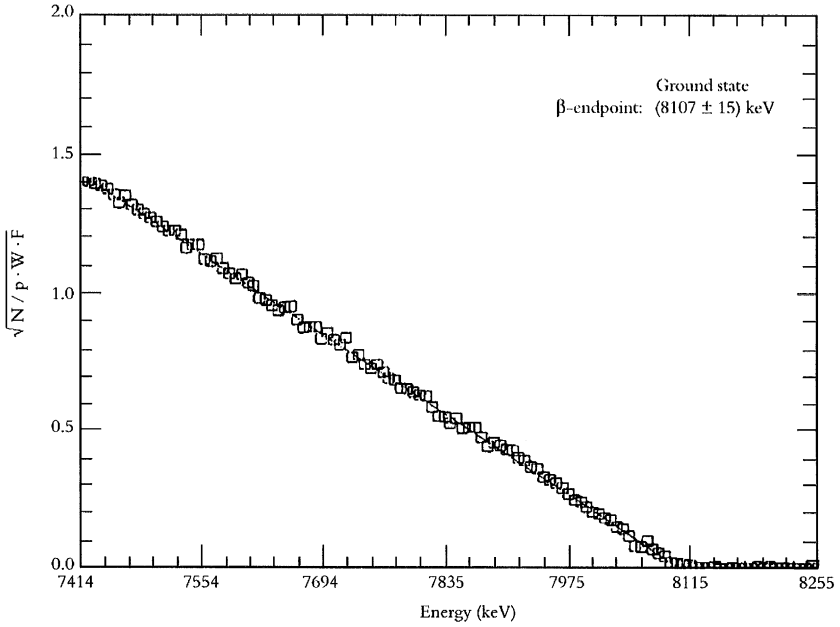

Fig. 10. β-endpoint spectrum of ^{92}Rb – Przewloka et al. (1992a); y-axis parameter represents quantification of the β spectrum in terms of electron momentum (N, p), Fermi (F) and decay-energy (W) functions as $\sqrt{N/pWF}$. [Reprinted by permission of Springer-Verlag from 'Measurements of β-endpoint energies using a magnetic electron separator' by Przewloka, M., Przewloka, A., Wächter, P., Wollnik, H., Z. Phys. A–Hadrons and Nuclei, **342**, 23–26. Copyright 1992 by Springer-Verlag, Tiergartenstr. 17, D-69121 Heidelberg, Germany].

spectroscopy revealed significant detail for 126 bound and 12 unbound levels of ^{87}Kr. An extremely complex decay scheme can be derived from these measurements: over 370 gamma-ray transitions are associated with the β^- decay mode and the excited states of ^{87}Kr, and all delayed neutrons are assumed to decay directly to the ground state of ^{86}Kr. The β^-n decay of ^{93}Rb is shown in Fig. 11, with the population of a number of excited states of ^{92}Sr that undergo subsequent gamma-ray de-excitation (Kratz et al., 1982); Greenwood and Caffrey (1985) have studied the delayed-neutron emissions to reveal a relatively complex spectrum (Fig. 12) and the possible population of as many as 25–30 unbound nuclear levels of ^{93}Sr.

The observation of line structure and measurements of the delayed-neutron spectra have aided considerably in defining the β^-n decay mode for a number of neutron-rich fission products. All of these studies have proved to be particularly fruitful. Many short-lived fission products that undergo β^-n decay need to be characterised in this manner, and so generate discrete beta-particle, delayed-neutron and gamma-ray data for this important decay mode.

4.2.3. Discrete decay data

The ion guide isotope separator (IGISOL) at the University of Jyväskylä has been successfully applied to the study of exotic nuclei produced by light-ion induced fusion and fission reactions (Penttilä et al., 1997). Charged-particle induced fission is an effective method of producing neutron-rich nuclides at high yield in the region $A \sim 100$. Half-lives, beta energies and branching fractions of a number of previously unknown delayed-neutron precursors have been determined from their neutron spectra (Lhersonneau et al., 1998). Nuclear level studies are also possible through the application of $\beta-\gamma-\gamma$ coincidence. For example, the decay of ^{110}Mo has been studied (half-life of 0.30(4) s) by a combination of multiscaled singles, $\beta-\gamma$-timed and $\gamma-\gamma$-timed coincidences (Lhersonneau et al., 1994). A reasonably detailed decay scheme was determined for this short-lived fission product, and this type of study is particularly relevant to the problem of determining the discrete decay data of such nuclides.

The laser isotope separator system on the ISOLDE facility has been used to isolate neutron-rich nuclides formed as pulse-emissions from spallation reactions on actinides (Kautzsch et al., 1998). Delayed-neutron and gamma-ray spectra were measured to obtain some of the discrete decay data of specific Ag nuclides (^{126,128,129}Ag, with half-lives of 92, 58 and 46 ms, respectively). Experiments with the OSIRIS mass separator have focused on determining the spin states and gamma-ray multipolarities of isomers of Te and In (Fogelberg et al., 1998). The 23/2- isomer of ^{125}In was the most short-lived fission product observed on this system at the time,

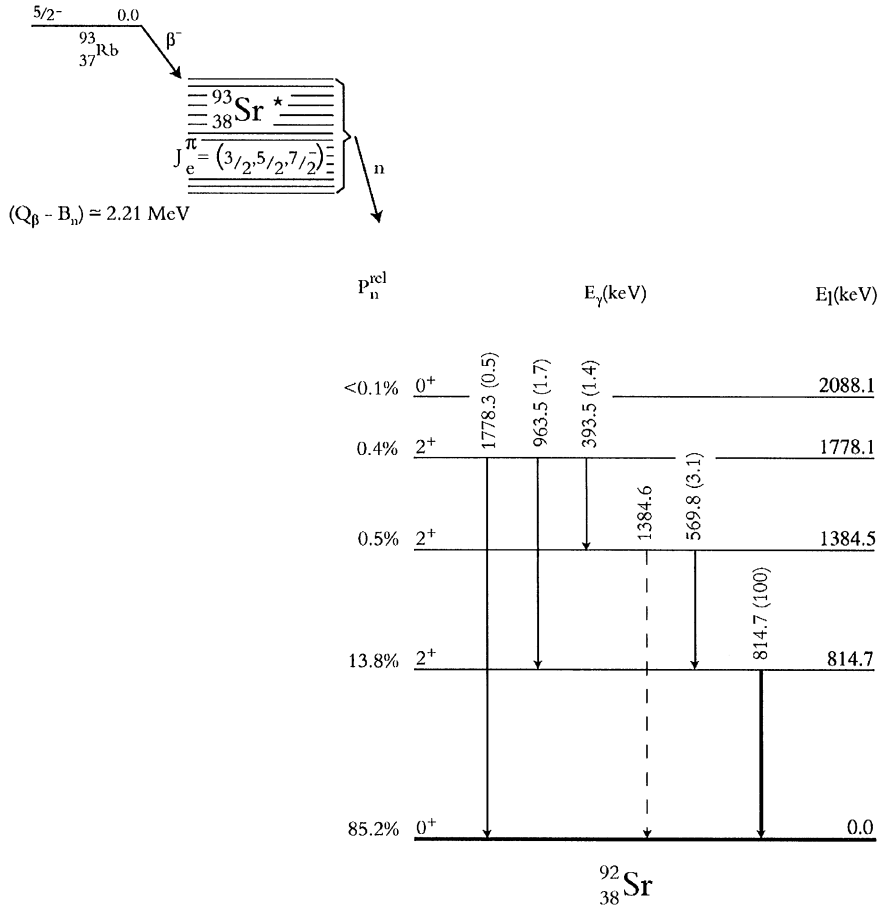

Fig. 11. Beta-delayed neutron decay scheme of ^{93}Rb to individual levels in ^{92}Sr nucleus; P_n^{rel}partial branching fractions are given as % of the total neutron emission probability (P_n^{tot}), and the γ-ray emission probabilities are quoted in parentheses relative to the strongest transition – Kratz et al. (1982). [Reprinted by permission of Springer-Verlag from 'Beta-delayed neutron emission from $^{93-100}$Rb to excited states in the residual Sr isotopes' by Kratz, K.-L., Schröder, A., Ohm, H., Zendel, M., Gabelmann, H., Ziegert, W., Peuser, P., Jung, G., Pfeiffer, B., Wünsch, K.D., Wollnik, H., Ristori, C., Crancon, J., Z. Phys. A – Atoms and Nuclei, **306**, 239–257. Copyright 1982 by Springer-Verlag, Tiergartenstr. 17, D-69121 Heidelberg, Germany].

undergoing de-excitation by a gamma-ray cascade (see Fig. 13, half-life of 5.0(15) ms). Further measurements by means of these dedicated facilities can be expected to generate extremely useful information in the formulation of consistent sets of decay data for short-lived fission products.

Nuclear structures of complex high-energy events have been studied with large arrays of Ge detectors interlaced by bismuth germanate Compton suppressors (BGO). Clover and honeycomb designs have been constructed to create EUROGAM, EUROBALL and GAMMASPHERE (Nolan et al., 1994): $\gamma-\gamma-\gamma$ coincidence systems have been developed with 14 to 20 Compton-suppressed arrays of Ge detectors (Figs. 14 and 15). The decay of many neutron-rich nuclei have been observed for the first time in the form of correlated fission fragments such as Sr–Nd, Zr–Ce and Mo–Ba nuclei. Since over 150 different radionuclides may be produced in spontaneous fission with yields greater than 0.1%, the large number of prompt and delayed gamma rays demand multifold coincidence studies in order to determine individual nuclear level schemes. This need has been realised with the evolution of a new generation of large-detector arrays. Prompt gamma-ray measurements have furnished information of yrast levels, while the study of the gamma rays that follow beta decay have contributed to the evolution of some of the more obscure decay schemes (Ahmad and Phillips, 1995; Hamilton et al., 1995). Fission yields can be obtained through the prompt gamma rays, while beta-decay parameters such as half-life, Q_β and transition probabilities can be determined by gating on suitable emissions. Such high-resolution studies of the gamma rays emitted by fission fragments can provide the desired

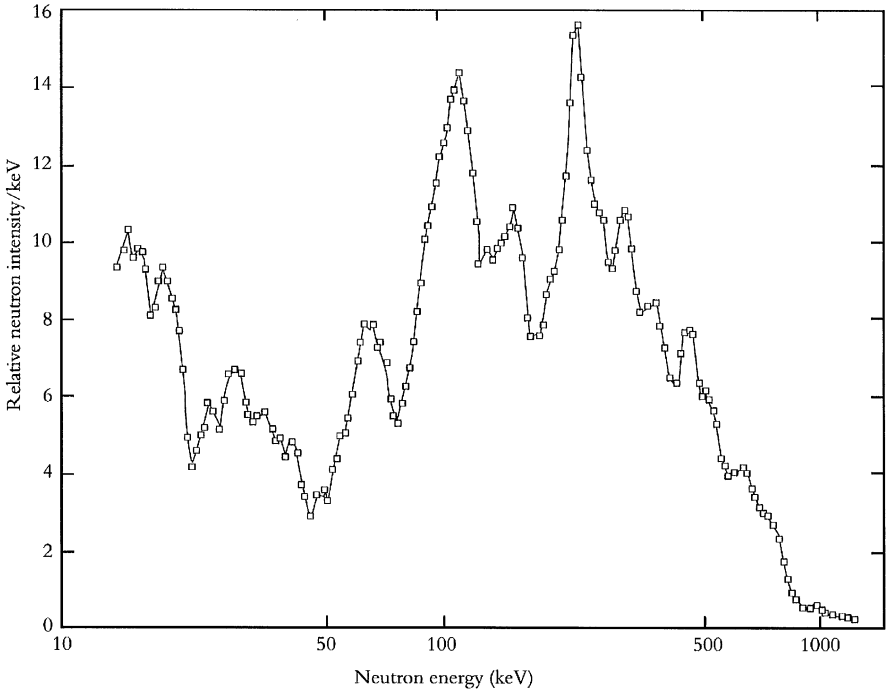

Fig. 12. Delayed–neutron spectrum of ^{93}Rb – Greenwood and Caffrey (1985). [Reprinted by permission of the American Nuclear Society from 'Delayed-neutron energy spectra of $^{93-97}$Rb and $^{143-145}$Cs' by Greenwood, R.C., Caffrey, A.J., Nucl. Sci. Engng., **91**, 305–323. Copyright 1985 by the American Nuclear Society, 555 N. Kensington Avenue, La Grange Park, IL 60526, USA].

decay data for short-lived fission products. Studies of fission sources and heavy-ion fusion-evaporation reactions by means of EUROBALL and GAMMASPHERE will enable the decay data of a significant number of short-lived radionuclides to be determined, and encourage sounder theories to be developed in the exploration of neutron-rich nuclei further beyond the line of stability than ever before (Lister, 2000; Warner, 2000).

5. Decay data libraries

Nuclear data files have been assembled over many years to assist analysts and spectroscopists to identify and quantify radionuclides. As the nuclear structures of these nuclides have been characterised in greater detail and their decay-scheme data defined with increased confidence, extended libraries of nuclear data have been compiled in agreed formats for direct application within the nuclear power industry, fuel reprocessing and waste management. These various libraries include recommended decay data that are updated at regular intervals through either international consensus, or more localised efforts based on specific national needs (Lemmel and Schwerer, 1998; Dunford and Burrows, 1999).

5.1. Evaluation procedures

Decay-data evaluators from within a number of national laboratories have combined forces to develop and expand the evaluation methodology implemented in the IAEA Co-ordinated Research Programmes (see Section 3), and outlined below.

If possible, no individual measurement is allowed to contribute more than 50% to the sum of weights when more than one value of the same parameter is reported, and the uncertainty of the datum is increased if necessary. If the set of accepted experimental data proves to be inconsistent, one of several possibilities could be adopted:

(i) recommend the unweighted mean;
(ii) change the weights;
(iii) 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).

An appropriate method of changing weights is preferred rather than outright rejection of data. If the reduced χ^2 is within the acceptable range (i.e., $\chi^2/(N-1)=2$, where N is the number of distinct measurements), the weighted mean is recommended

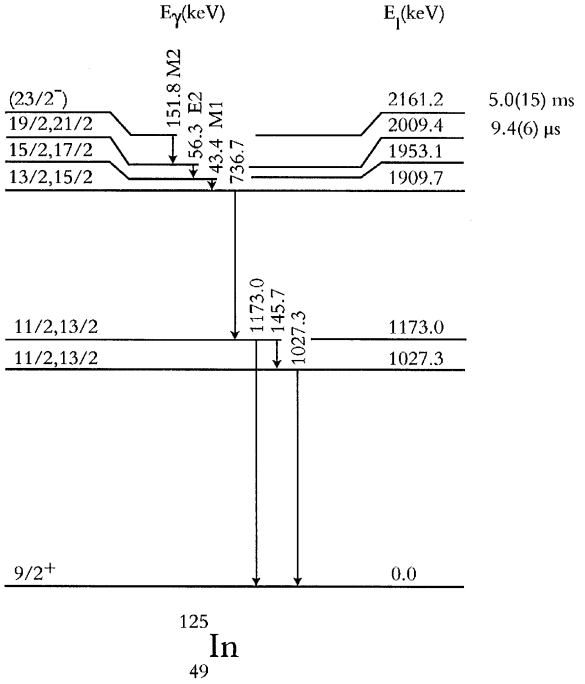

Fig. 13. Decay scheme of 5 ms isomer of ^{125}In – Fogelberg et al. (1998). [Reprinted by permission of the American Institute of Physics (AIP) from 'New high spin isomers obtained in thermal fission' by Fogelberg, B., Mach, H., Gausemel, H., Omtvedt, J.P., Mezilev, K.A., AIP Conference Proceedings 447, pp. 191–195. Copyright 1998 by the American Institute of Physics, 500 Sunnyside Boulevard, Woodbury, NY 11797-2999, USA].

as the evaluated value. However, if the data set reveals inconsistencies after adjustment (i.e., $\chi^2/(N-1) > 2$), the choice of either the weighted or unweighted mean depends on whether or not the error bars (expressed as one standard deviation) on each mean encompasses the other.

Combined with the above procedure, an evaluation strategy can be adopted that includes a series of data manipulations:

(i) all decay modes of each radioactive nuclide are specified in terms of both the branching fractions and Q-values;
(ii) sum of all α, β^-, EC/β^+ and isomeric gamma-ray emission probabilities are consistent with the corresponding branching fractions;
(iii) gamma-ray emission probabilities must be the photon probabilities per disintegration;
(iv) when the internal conversion of a gamma-ray transition is significant, theoretical internal conversion coefficients are adopted if experimental data are unavailable;
(v) internal conversion coefficients for gamma-ray transitions should be consistent with both the photon and total transition probabilities, i.e., (photon + conversion electron) emission probabilities = total transition probability;
(vi) every effort should be made to ensure that there is a reasonable balance between the population and depopulation of all excited levels in a decay scheme;

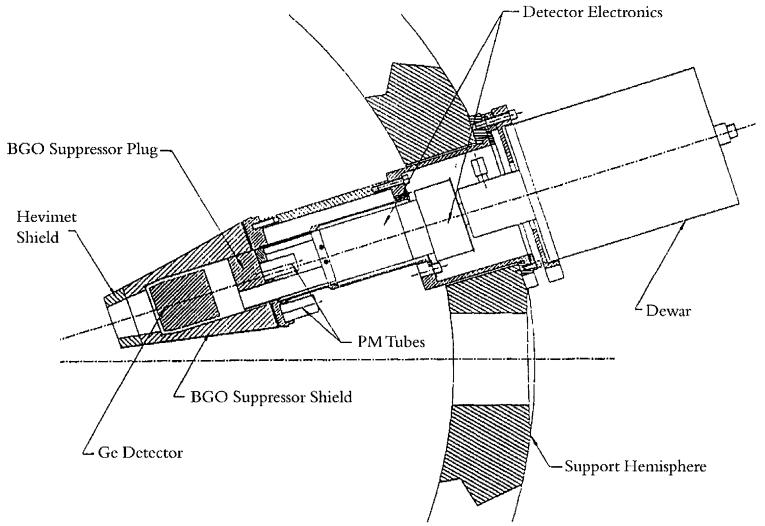

Fig. 14. Escape-suppressed Ge detector used in the γ-detector arrays of GAMMASPHERE — Nolan et al. (1994). [Reprinted with permission from the Annual Review of Nuclear and Particle Science, 'Large arrays of escape-suppressed gamma-ray detectors' by Nolan, P.J., Beck, F.A., Fossan, D.B., **45**, 561–607. © 1994 by Annual Reviews www.AnnualReviews.org].

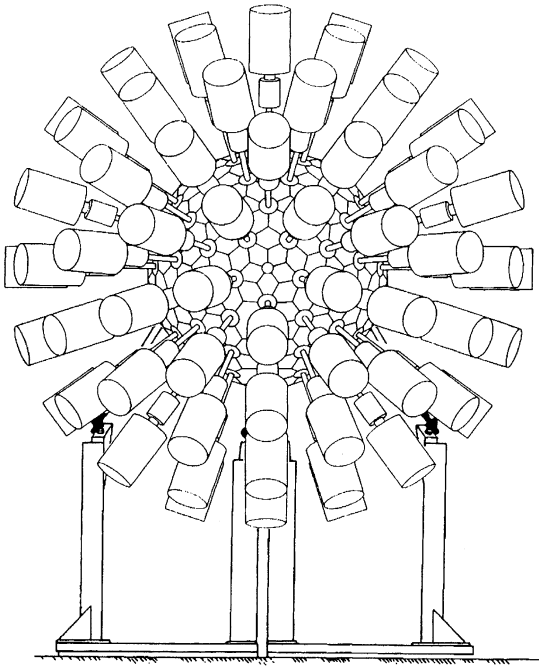

Fig. 15. γ–detector array of GAMMASPHERE — Nolan et al. (1994). [Reprinted with permission from the Annual Review of Nuclear and Particle Science, 'Large arrays of escape-suppressed gamma-ray detectors' by Nolan, P.J., Beck, F.A., Fossan, D.B., **45**, 561–607. © 1994 by Annual Reviews www.AnnualReviews.org].

(vii) the type of beta transition has to be taken into account when calculating the mean beta energies from the evaluated endpoints;
(viii) energies and emission probabilities of conversion electrons, Auger electrons, X-rays and annihilation radiation must be derived in a consistent manner.

When necessary, the theoretical internal conversion coefficients tabulated by Band et al. (1976), Hager and Seltzer (1968), and Rösel et al. (1978) should be used in conjunction with the evaluated gamma-ray data. Nuclear binding energies and Q-values can be obtained from the tabulations of Audi and Wapstra (1995), while X-ray data can be taken from Salem et al. (1974) or Firestone et al. (1996, pp. F40–F53). The evolution of a consistent and reasonably comprehensive decay scheme may involve the postulation of some transitions that have not been experimentally observed; for example, beta-particle and electron-capture transitions may have to be calculated from the relative gamma-ray transition probabilities and normalisation factor, since these "missing" data are important in estimating the mean beta energy per decay.

Under certain circumstances, an applications library needs to contain decay data that are complete and consistent (e.g., to model decay heat as a function of time after termination of the fission process). The normal procedure would be to evaluate and prepare individual files of decay data that have been internally tested for consistency between the various decay-scheme parameters (i.e., α, β and γ transitions), and to validate the complete library against a series of benchmarking experiments. Decay-scheme consistency evolves during the course of evaluating spectral measurements, and every effort should be made to produce comprehensive data sets. The consistency of the recommended data can be determined by calculating the percentage deviation between the effective Q-value and the calculated Q-value:

(i) $$\text{effective Q-value} = \sum_{i=1}^{\text{all BF}} Q_i \, \text{BF}_i$$

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

(ii) $$\text{calculated Q-value} = \sum_{i}^{\text{all }\alpha} E_{\alpha_i} \, P_{\alpha_i} + \sum_{j}^{\text{all }\beta} E_{\beta_j} \, P_{\beta_j} + \sum_{k}^{\text{all }\gamma} E_{\gamma_k} \, P_{\gamma_k} + \sum_{l}^{\text{all X-rays}} E_{\text{X1}} \, P_{\text{X1}} + \cdots,$$

where E_{α_i}, E_{β_j}, E_{γ_k}, E_{X1}, etc and P_{α_i}, P_{β_j}, P_{γ_k}, P_{X1}, etc. are the energies and emission probabilities of the ith alpha particle, jth beta particle, kth gamma ray, lth X-ray, etc. of the individual decay process.

$$\text{Consistency (percentage deviation)} = \left[\frac{(\text{effective } Q\text{-value}) - (\text{calculated } Q\text{-value})}{(\text{effective } Q\text{-value})}\right] \times 100.$$

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. Not all libraries include this form of consistency check. Furthermore, while there are merits in undertaking such a statistical analysis, subsequent adjustments to achieve consistency may not always be appropriate.

The resulting decay-data file for a particular radionuclide should include a comments section in which any problems encountered during the evaluation can be described. If the resulting decay scheme has any outstanding problems, a statement can be made to the effect that further measurements are required.

5.2. Libraries of nuclear structure data

A number of groups around the world are engaged in the co-ordinated evaluation and compilation of nuclear data. Basic nuclear physics and structure data are

regularly evaluated by the International Network for Nuclear Structure Data Evaluation under the auspices of the International Atomic Energy Agency to generate updated Evaluated Nuclear Structure Data Files (ENSDF). This network is responsible for the evaluation of all mass-chains on a regular basis (National Nuclear Data Centre, 1987; Bhat, 1992), and the resulting files are maintained by the National Nuclear Data Centre (NNDC) at Brookhaven National Laboratory along with other services (Dunford, 1994; Kinsey et al., 1994). Available databases include ENSDF (evaluated nuclear structure data), atomic masses, NuDat (basic nuclear data extracted from ENSDF, including radionuclidic decay data), RADLST (calculated decay radiations from ENSDF), CSISRS (experimental cross-section data) and ENDF (evaluated nuclear reaction and decay data in ENDF-6 format for nuclear power and other applications). The NNDC Website is accessed via:

http://www.nndc.bnl.gov

and the desired database can be inspected by following the appropriate instructions associated with data retrieval. This on-line data service gives access to the ENDF-6 nuclear reaction and decay-data files developed in the 1980s for reactor applications (Dunford, 1992): these discrete decay data have been supplemented with the mean beta and gamma energies and P_n values determined by Rudstam et al. (1990, 1993) and theoretical decay data for a significant number of short-lived fission products (Brady and England, 1989; Katakura and England, 1991).

NUBASE contains the main decay properties of nuclides in their ground and isomeric states (Audi et al., 1996, 1997). These data have been primarily derived from ENSDF and the atomic mass evaluation of Audi and Wapstra (1995). Experimentally determined nuclear parameters have been compiled for 3010 nuclides, with some values estimated by extrapolation:

> mass excess, excitation energies of isomeric states, half-life, spin and parity, decay modes and branching fractions, isotopic abundances of stable nuclei, and relevant references.

The NUBASE file can be retrieved electronically from the Atomic Mass Data Centre through the Internet:

http://csnwww.in2p3.fr/amdc/

The Table of Isotopes has a long and respected history, culminating in the release of the eighth edition (Firestone et al., 1996). A CD-ROM is also included that contains all of the recommended decay-scheme data, and this vehicle will be preferentially used to make updates (Firestone et al., 1998). The main table is initially ordered by mass number and then by atomic number, with abbreviated mass-chain decay schemes that give the adopted half-lives, spin-parity and Q-values. Tabulated data are given for each ground state and isomer with half-lives $\geqslant 1$ s. Extended level schemes are also shown for each radionuclide for which there is more detailed information than shown in the mass-chain decay scheme. Recommended decay data from the ENSDF evaluations have been adopted whenever the authors judged this source to be appropriate. Significant amounts of nuclear data are contained within this immense publication, and the reader is referred to the original volumes for greater detail.

Numerous decay-data compilations have been assembled for spectroscopic applications (e.g., Reus and Westmeier, 1983; Westmeier and Merklin, 1985; Rytz, 1991; Nichols, 1996). However, few appear to be maintained in the same rigorous manner as ENSDF and the Table of Isotopes, which contain decay data for approximately 2500 radionuclides and cover effectively all nuclides that have been characterised to a reasonable extent; the ability to inspect and use these data via CD-ROM and the World Wide Web also adds considerable strength to their commonality of use.

5.3. Nuclear applications libraries

The Joint Evaluated File (JEF) is a collaborative project between member countries of the NEA Data Bank to produce a nuclear data library for industrial applications and research (Nordborg et al., 1992; Nordborg and Salvatores, 1994). Various decay-data files have been assembled via a combination of evaluation and direct adoption from other sources (particularly NUBASE, ENSDF, UKPADD (Nichols, 1993) and UKHEDD (Nichols, 1991)). The JEF-2.2 library consists of a general purpose file (neutron cross-section data), radioactive decay-data files and a fission yields file. The contents of the JEF-2 decay-data files have been summarised in hardcopy, and represent a definitive data set for nuclear applications (JEF-2.2 radioactive decay data, 1994). The NEA Data Bank can be accessed via the Internet:

http://www.nea.fr

followed by clicking on the options 'Data Bank' and 'Nuclear Data Services'. New users are required to register electronically under the 'Registration' option, where a password will be provided (although access to information other than the databases is open to everyone without the need for a password).

Activation calculations for fusion devices require a combination of cross sections and a reasonably comprehensive set of decay data. Hence, the European Activation System (EASY) has been assembled to undertake this type of study by means of the EAF

nuclear data library and the FISPACT inventory code (Forrest, 1994). All decay data are for radionuclides of relevance to fusion, with a large number of activation products that arise from the proposed structural materials. Isomeric states are important in these activation calculations because they become targets in multi-step reactions after their formation. The EAF decay-data library continues to be developed and improved through a series of agreed evaluations (Forrest and Sublet, 1998; Backhouse and Nichols, 1998).

Efforts are underway to amalgamate the JEF and EAF libraries, and to improve and expand the contents of the resulting files as a joint programme. Thus, a Joint Evaluated Fission and Fusion project has been formulated to combine the JEF and EAF database activities. The new library (JEFF-3) will contain a general purpose file of neutron cross-section data and special purpose files of fission yields and decay data (Finck et al., 1997). Specific studies have been made to improve and develop those decay-data files judged to be previously inadequate (Backhouse and Nichols, 1998; Nichols et al., 1999a). The discrete decay data for 37 fission-product radionuclides have been re-evaluated from published measurements, and various decay parameters and continuum spectra were theoretically derived for an additional 35 neutron-rich nuclides judged to be important in decay-heat calculations. Decay data for approximately 50 radionuclides within EAF were also identified as inadequate, and new files have been prepared for these nuclides. Modifications and improvements to the UK decay-data files will continue, and the resulting evaluations will be used as a first step towards the development of JEFF-3 (Nichols et al., 1999b).

Other libraries have been developed for nuclear power applications that contain decay-data files. Staff at the Chinese Nuclear Data Centre have assembled a library of basic nuclear data and model parameters (Su Zongdi et al., 1994, 1997). This nuclear parameter library (CENPL) contains atomic masses and constants for ground states, nuclear level properties and gamma-ray data extracted from ENSDF.

The JNDC-FP (Japanese Nuclear Data Committee — Fission Product) library contains decay and fission yield data for 1080 unstable and 147 stable fission products, and neutron cross-section data for 166 nuclides (Tasaka et al., 1990). Recommended decay data include half-lives, branching ratios, and total beta and gamma-ray energies released per decay of each unstable radionuclide. Theoretical and experimental values of the mean beta- and gamma-decay energies have been assessed for each nuclide, and the most reliable values have been chosen (Yoshida and Nakasima, 1981). Comparisons have also been made between decay-power curves derived from the library by calculation and measurements performed at various laboratories on a variety of fissile materials (Yoshida et al., 1999; Yoshida and Tachibana, 2000). Improved agreement was observed when theoretical beta-decay data were incorporated into the library, particularly for decay-heat calculations up to 10 s and between 300 and 3000 s after the fission process had been terminated (where anomalies between calculations and experiments have been previously noted).

Decay data have been compiled as part of the Fusion Evaluated Nuclear Data Library, version 2.0 (FENDL-2.0), which was released in 1999 through the IAEA Nuclear Data Section (Forrest and Mann, 1997). The nuclear decay data for 1867 radionuclides have been assembled on a CD-ROM (IAEA-NDS-CD-06) covering decay type, energy and half-life. This sub-library is based on the EAF decay files, and complements the activation cross-section data contained within the FENDL-2.0 library.

5.4. *Electronic access through CD-ROMs and the Internet*

The advent of personal computers (leading to the ubiquitous CD and the Internet) has revolutionised the ability to communicate with and access large databases rapidly and efficiently. Examples of the provision of CD-ROMs and the implementation of Websites have been noted earlier (for example, ENSDF, NUBASE, FENDL-2.0 and the Table of Isotopes). A significant number of these databases have been adapted so that PCs can interrogate, compare and extract their contents. Specific systems are described below, although the author lays no claim to a comprehensive study of these aids.

The GAMCAT database was assembled by Tepel and Müller (1990) for PC interrogation and retrieval of the desired parameters for information and subsequent use. This library consists of a nuclide file of 2587 entries, a gamma-ray file of approximately 50 000 lines, and an alpha-particle file of approximately 2000 lines. Decay data for individual radionuclides can be displayed in various tabulated forms as defined by the user.

Chu et al. (1997) have developed a Web server to transfer ENSDF data and references to home pages and to the Isotope Explorer. This powerful system acts as a substitute for the Table of Isotopes CD-ROM (Firestone et al., 1996). Data can be retrieved for a nuclide, and displayed in the form of a decay scheme, tables and parameter plots. Another module has been designed to highlight specific decay parameters in a similar format to the Chart of the Nuclides.

The NuDat program is available through the Websites of the Nuclear Data Centres to extract nuclear data from several databases (including thermal-neutron cross sections, ENSDF and the data sets generated by RADLST). Remote searches can be implemented for a wide range of parameters within the files through

specific identifiers such as chemical symbol, atomic number and mass number; nuclear structures can also be interrogated on the basis of nuclear level properties (e.g., spin-parity, energy and multipolarity). The data of interest can be written to a personal file and sorted prior to producing a hard-copy listing. There are many other features to this program, and greater detail can be found in the appropriate reports (Kinsey, 1996 (available on NNDC Website); Dunford and Burrows, 1999). The PARADOX management program has also been applied to the nuclear structure and decay data files of ENSDF by Boboshin et al. (1994); relevant data can be extracted to address both fundamental and applied activities.

Equivalent work under the auspices of the NEA Data Bank has focused on the JEF-PC program for the display of nuclear data from the JEF library (Konieczny et al., 1994, 1997). The first CD-ROM version of JEF-PC was released in 1994, and allowed the user to display neutron cross sections (0–20 MeV) for 313 nuclides, decay data for 2345 radionuclides, and fission yields for 21 fissile materials. A display of the Chart of the Nuclides acts as the interface for selecting nuclides of interest, leading on to summaries of the recommended decay data (such as mass, half-life, mean decay energies, Q-values and branching fractions of decay modes) and listings of alpha, beta, EC and gamma-ray transitions. Some of the data can also be presented in spectral form. Additional options make JEF-PC a powerful package that will continue to be developed and improved.

Dedicated catalogues of gamma-ray spectra have been assembled and improved over 50 yr to assist greatly in the characterisation and quantification of the radioactive content of materials. Extensive efforts have been made to measure systematically the gamma-ray emissions of individual radionuclides by means of NaI(Tl) scintillation, Si(Li), Ge(Li) and HPGe detectors, and these spectra have been collected together in various forms and circulated widely to assist in spectroscopic analyses (Heath, 1974; Helmer et al., 2000). With the advent of CD-ROMs and the Internet, the opportunity has arisen to furnish these gamma-ray spectrum catalogues in an electronic form for direct access, along with several significant enhancements. Individual peaks have been colour-coded: strong peaks are red, while annihilation and coincidence sum peaks are highlighted in orange. Tables have also been assembled that list half-lives, and gamma-ray energies and emission probabilities extracted from ENSDF. Additional features include simplified decay-chain diagrams and partial decay schemes, in which the latter include all gamma rays observed in the original spectrum. As with a number of other CD-ROM systems, this extensive catalogue can be accessed through the Website:

http://id.inel.gov/gamma

to provide spectroscopists with an extremely rapid and powerful means of identifying individual radionuclides. Proposed developments include combined spectra to imitate the activation of mixed sources rather than separated radionuclides, and prompt gamma-ray spectra from thermal-neutron capture.

"Nuclides 2000" was developed by Magill (1999), and has been issued as a CD-ROM. The Nuclide Explorer gives fast access to the radionuclide decay data taken from JEF-2.2, using either a periodic table display or Segrè chart, and selecting the desired nuclear property. Derived data include activities, gamma dose rate and annual limits of intake. Additional features include background articles that describe various aspects of radioactive decay and historically relevant publications. More information on "Nuclides 2000" is available from the Website:

http://www.nuclides.net/

The Spanish National Reference Database for Ionizing Radiations is in the process of being formulated and prepared for access through the Internet and from a CD-ROM (Los Arcos et al., 2000). Sets of evaluated and calculated decay parameters have been assembled to form the initial database entitled Base Nacional de Datos de Referencia para Radiaciones Ionizantes (BANDRRI), which has been designed with the following aims:

(i) provide, for national use, recommended reference values of nuclear parameters for radioactive decay and dosimetry applications;
(ii) all data traceable to international databases;
(iii) simplified procedures for remote access to bibliographies and databases.

The contents of BANDRRI include radionuclidic decay data, atomic data, and dosimetry parameters that can be conveniently accessed through the Website:

http://www.ciemat.es/bandrri

Only a limited number of radionuclides and materials have been stored in the database, but the contents will be expanded in the future. The resulting interactive process generates the nuclear decay schemes of the individual radionuclide, energies and de-excitation of nuclear levels, and the energies and emission probabilities of the various radiations and transitions. Furthermore, the PC mouse can be used to highlight specific features of the decay scheme depicted on the screen in order to generate the stored values of individual parameters (e.g., energy and emission probability of a particular transition).

Under the auspices of the International Committee for Radionuclide Metrology, evaluations are being

undertaken for a number of important radionuclides. This work also generates input data to the continued development of the LPRI Table de Radionucléides (Lagoutine et al., 1982-87; Bé et al., 1996), which is entitled "Nucléide" and has been prepared as a CD-ROM. These data cover a select number of radionuclides defined as important in metrology and various applications, such as nuclear medicine, environmental monitoring and standards for detector calibration. A well-defined evaluation procedure has been followed, and the recommended decay data are of high quality. The status of the on-going work at the end of March 2000 is summarised in Table 17.

A combination of the PC and CD-ROM represents a particularly powerful vehicle for an information explosion that has been applied with considerable success to the provision and communication of recommended decay data. The number of CD-ROM based systems has increased substantially in recent years; a comprehensive list would prove difficult to compile, would rapidly become outdated, and therefore has not been attempted in this review.

5.5. Network of nuclear data centres

The Nuclear Data Network consists of five primary centres:

National Nuclear Data Centre (NNDC), Brookhaven National Laboratory, USA;
Nuclear Energy Agency (NEA), Issy-les-Moulineaux, France;
International Atomic Energy Agency (IAEA), Vienna, Austria;
Institute of Physics and Power Engineering (IPPE), Obninsk, Russia;
Kurchatov Institute, Moscow, Russia,

and a number of specialised data laboratories:

Chinese Nuclear Data Centre, China Institute of Atomic Energy, Beijing, China;
Japan Atomic Energy Research Institute, Nuclear Data Centre, Tokai-Mura, Japan;
RIKEN Nuclear Data Group, Saitama, Japan;
Japan Charged-Particle Nuclear Reaction Data Group, Hokkaido University, Sapporo, Japan;
KAERI Nuclear Data Evaluation Laboratory (KAERI/NDEL), Yusong, Republic of Korea;
Centre for Photonuclear Experimental Data, Moscow State University, Russia;
Nuclear Data Group, Russian Federal Nuclear Centre, Sarov, Russia;
Ukraine Nuclear Data Centre, Institute for Nuclear Research, Kiev, Ukraine;
ATOMKI Charged-Particle Nuclear Reaction Data Group, Debrecen, Hungary

Table 17
ICRM decay data evaluation project (DDEP) – status of evaluations, March 2000

Radionuclide	Evaluation centre[a]	Status[b]
^{3}H (12.32 yr)	KRI	Published (1999)
^{7}Be (53.29 d)	INEEL, PTB	Completed
^{14}C (5700 yr)	KRI	Published (1999)
^{22}Na (2.6027 yr)	INEEL, PTB	Published (1999)
^{24}Na (14.951 h)	INEEL, PTB	Completed
^{26}Al (7.17×10^{5} yr)	LBNL	Published (1999)
^{35}S (87.32 d)	LNHB, KRI	Published (1999)
^{36}Cl (3.01×10^{5} yr)	KRI	Published (1999)
^{40}K (1.265×10^{9} yr)	INEEL	Published (1999)
^{44}Sc (3.97 h)	LBNL	Completed
^{46}Sc (83.79 d)	INEEL	Under review
^{44}Ti (60 yr)	LBNL	Completed
^{51}Cr (27.7025 d)	INEEL, PTB	Completed
^{54}Mn (312.11 d)	PTB, INEEL	Completed
^{56}Mn (2.5789 h)	AEA	Work in progress
^{55}Fe (2.741 yr)	LNHB	Published (1999)
^{60}Fe (1.5×10^{6} yr)	LBNL	Completed
^{57}Co (271.74 d)	KRI	Work in progress
^{58}Co (70.83 d)	LNHB	Published (1999)
^{60}Co (5.271 yr)	INEEL	Published (1999)
^{57}Ni (35.60 h)	LBNL	Completed
^{65}Zn (244.06 d)	INEEL	Published (1999)
^{67}Ga (3.2612 d)	KRI	Work in progress
^{68}Ga (67.71 m)	PTB	Published (1999)
^{68}Ge (270.95 d)	PTB	Published (1999)
^{75}Se (119.79 d)	LBNL, PTB	Published (1999)
^{85}Sr (64.84 d)	PTB	Completed
^{89}Sr (50.53 d)	PTB	Under review
^{88}Y (106.65 d)	PTB	Under review
^{95}Zr (64.032 d)	INEEL	Published (1999)
^{93m}Nb (16.13 yr)	KRI	Work in progress
^{95}Nb (34.991 d)	INEEL	Published (1999)
^{95m}Nb (3.61 d)	INEEL	Published (1999)
^{99}Mo (2.7475 d)	LNHB	Work in progress
^{99}Tc (2.11×10^{5} yr)	LNHB	Work in progress
^{99m}Tc (6.01 h)	LNHB	Work in progress
^{109}Cd (1.263 yr)	PTB	Completed
^{111}In (2.8047 d)	KRI	Published (1999)
^{113m}In (1.658 h)	INEEL, LNHB	Published (1999)
^{113}Sn (115.09 d)	INEEL	Published (1999)
^{125}Sb (2.7586 yr)	CIEMAT, UNED	Work in progress
^{123m}Te (119.5 d)	LNHB, PTB	Published (1999)
^{125m}Te (57.40 d)	CIEMAT, UNED	Work in progress
^{125}I (59.407 d)	PTB	Published (1999)
^{129}I (1.57×10^{7} yr)	KRI	Work in progress
^{137}Cs (30.018 yr)	INEEL, PTB	Published (1999)
^{133}Ba (10.538 yr)	KRI	Work in progress
^{140}Ba (12.752 d)	INEEL	Under review
^{140}La (1.6781 d)	INEEL	Under review
^{139}Ce (137.64 d)	PTB, INEEL	Published (1999)
^{141}Ce (32.508 d)	PTB	Published (1999)
^{143}Pr (13.57 d)	BNL	Completed
^{153}Sm (1.9285 d)	INEEL	Completed
^{154}Eu (8.592 yr)	KRI	Work in progress
^{155}Eu (4.7611 yr)	KRI	Work in progress
^{153}Gd (240.4 d)	INEEL	Completed

Table 17 (*continued*)

Radionuclide	Evaluation centre[a]	Status[b]
^{166}Ho (26.763 h)	PTB	Work in progress
^{166m}Ho (1.2×10^3 yr)	PTB	Work in progress
^{170}Tm (128.6 d)	KRI	Work in progress
^{169}Yb (32.026 d)	LNHB, PTB	Under review
^{186}Re (3.7183 d)	PTB	Completed
^{188}Re (17.005 h)	LBNL	Published (1999)
^{192}Ir (73.827 d)	LBNL	Published (1999)
^{194}Ir (19.28 h)	LBNL	Published (1999)
^{198}Au (2.6952 d)	PTB	Under review
^{203}Hg (46.612 d)	AEA	Work in progress
^{201}Tl (72.912 h)	PTB	Completed
^{207}Bi (32.9 yr)	LNHB	Published (1999)
^{241}Am (432.2 yr)	KRI	Work in progress
^{252}Cf (2.645 yr)	LNHB	Work in progress

[a] AEA — AEA Technology, Harwell, UK,
BNL — Brookhaven National Laboratory, Upton, NY, USA,
CIEMAT — Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Madrid, Spain,
INEEL — Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID, USA,
KRI — Khlopin Radium Institute, St. Petersburg, Russia,
LBNL — Lawrence Berkeley National Laboratory, Berkeley, CA, USA,
LNHB — Laboratoire National Henri Becquerel (ex-LPRI), Saclay, France,
PTB — Physikalisch-Technische Bundesanstalt, Braunschweig, Germany,
UNED — Universidad Nacional a Distancia, Madrid, Spain.

[b] Published (1999): Table de Radionucléides, Laboratoire Primaire des Rayonnements Ionisants, CEA, Saclay, February1999, ISBN 2-7272-0200-8.

complement the core centres by assuming particular responsibility for the collection and dissemination of specialised data. Technical meetings are held between staff to discuss new ideas, data formats and customer services (Nordborg et al., 1997). The data centres also co-operate on the development of computer software for on-line and local access to the various data files.

Work-sharing within the network is carefully organised, and is based on geographical divisions:

USA and Canada	National Nuclear Data Centre (NNDC), Brookhaven National Laboratory, USA,
NEA member countries (except USA and Canada)	Nuclear Energy Agency (NEA) Data Bank, Issy-les-Moulineaux, France,
former Soviet countries	Institute of Physics and Power Engineering Data Centre (CJD), Obninsk, Russia,
rest of the world, not covered by any of the other centres	International Atomic Energy Agency (IAEA), Nuclear Data Section, Vienna, Austria.

Each centre undertakes other activities of benefit to the nuclear data community:

National Nuclear Data Centre (NNDC), Brookhaven National Laboratory, USA	• co-ordinate ENDF/B evaluations and maintain ENDF checking codes, • evaluate and maintain Evaluated Nuclear Structure Data File (ENSDF), • compile and maintain Nuclear Science References file.
Nuclear Energy Agency (NEA) Data Bank, Issy-les-Moulineaux, France	• co-ordinate Joint Evaluated Fission and Fusion Files (JEFF), • co-ordinate International Evaluation Co-operation, • collect, verify and disseminate computer programs.
International Atomic Energy Agency (IAEA), Nuclear Data Section, Vienna, Austria	• co-ordinate Fusion Evaluated Nuclear Data File (FENDL), • co-ordinate activities in the field of atomic and molecular data, • Co-ordinated Research Programmes to improve important nuclear data.
Institute of Physics and Power Engineering (IPPE), Obninsk, Russia	• maintain Russian evaluated nuclear data files (BROND), • neutron data.
Japan Atomic Energy Research Institute, Tokai-Mura, Japan	• maintain Japanese Evaluated Nuclear Data Library (JENDL).
Chinese Institute of Atomic Energy, Beijing, China	• maintain Chinese Evaluated Nuclear Data Library (CENDL).

The primary data centres have been able to develop efficient and direct on-line services to their customers as a consequence of the spectacular development of the Internet.

Bibliographic, experimental and evaluated reaction data are directly available, as well as nuclear structure and decay data. The Internet addresses for the main centres are:

National Nuclear Data Centre (NNDC), USA	http://www.nndc.bnl.gov
Nuclear Energy Agency (NEA), France	http://www.nea.fr

International Atomic Energy Agency (IAEA), Austria	http://www-nds.iaea.or.at

When searching for decay data, the reader should contact one of the data centres indicated above, in order to make sure that they receive the correct and most up-to-date information and nuclear data.

6. Concluding remarks

The majority of decay-data measurements and evaluations have become intricately entwined with the most important issues that require resolution in nuclear and non-nuclear applications. A primary aim is to improve metrology capabilities and generate data that can be applied with greater confidence in various technical fields. Requests for new measurements have become increasingly dependent on the results of evaluations to identify inconsistencies, anomalies and gaps in the desired data. A healthy synergy has been established in recent years so that many spectroscopic laboratories carry out decay-data work of direct relevance to the environmental, medical and industrial sectors.

Basic research into nuclear structure has moved towards the development of relatively complex detector systems to measure gamma cascades emitted by short-lived radionuclides and determine yrast levels through the detection of prompt gamma rays. This area of work is particularly challenging, and provides considerable insight into the fundamental features of nuclear structure. However, much remains to be explored in the formation and characterisation of neutron-rich nuclei from the fission process and in the fusion of deformed nuclei.

The communication of data between laboratories has improved beyond all recognition over the previous 10 yr. Both the Internet and utilisation of the CD-ROM have resulted in rapid access to the most recently evaluated decay data. Furthermore, the various Nuclear Data Centres around the world are designed to forge strong links and ensure that nuclear data needs can be addressed and satisfied in the most efficient manner. The author has difficulty in imagining where future developments in the various forms of electronic communications will lead to in another 10 yr. High-density storage media will soon be able to assist in the communication of scientific information in rather dramatic quantities. For example, DVD (digital versatile (or video) discs) will have a considerable impact on data storage and retrieval procedures because of their eight-fold increase in density compared with CD-ROMs. Single- and double-sided DVD media have storage capacities of 2.6 and 5.2 Gbytes, respectively; all of the libraries within a Nuclear Data Centre (and more) could be stored by and accessed from such a device. The updating and communication of extremely large arrays of data will pose handling problems, and some thought is required to operate these systems interactively through the Internet as required. One of the most practical approaches at the beginning of the 21st century is the distribution of comprehensive data libraries by CD-ROM (and DVD), with the appropriate software to download incremental updates from the Websites of the various data centres.

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Appendix

The parameters listed below represent a reasonably complete set of symbols used to denote the various decay processes and their associated emissions. Although some of these terms are only referred to briefly within this review (e.g., secondary radiations), they have been included to create a comprehensive compendium, and assist the reader with the contents of other texts.

General terms

A	(1) mass number of atom ${}^{A}_{Z}X_{N}$ ($A = N + Z$) (2) activity
N	(1) number of neutrons in atom ${}^{A}_{Z}X_{N}$ (2) number of radioactive atoms (in activity calculations) (3) number of distinct measurements (in reduced χ^2 calculations)
Z	atomic number (protons) in atom ${}^{A}_{Z}X_{N}$
max	maximum
J	total angular momentum quantum number
L	orbital angular momentum quantum number
S	spin quantum number
π	parity

t	time (e.g., in activity calculations)
$t_{1/2}$	radioactive half-life
$(t_{1/2})_i$	partial half-life
ft	comparative half-life (normally expressed in terms of log ft)
λ	decay constant
m	mass of particle
M_N	mass of the nucleus
M_α	mass of the alpha particle
m_0	rest mass of the electron
c	velocity of light
F	hindrance factor for α transition
n_K, n_L	mean number of vacancies in K and L shells
n_{KL}	number of L vacancies created by $K \rightarrow L$ transfer
B_K, $B_{L1}, \ldots$	exchange factor for K shell, L_1 sub-shell etc
C_n	shape factor for beta transition
C_0	shape factor for an allowed beta transition
f_0	Fermi integral for an allowed transition
$f_1, f_2, \ldots$	Fermi integrals for unique first forbidden, second forbidden etc. ($f_{\Delta J-1}$)
g	radial function of the electron
K, L, M,...	electron shells
K/L	abbreviation of $P_{ceK}/P_{ceL} = \alpha_K/\alpha_L$
K/LM	abbreviation of $P_{ceK}/(P_{ceL} + P_{ceM}) = \alpha_K/(\alpha_L + \alpha_M)$
K/LMN	abbreviation of $P_{ceK}/(P_{ceL} + P_{ceM} + P_{ceN}) = \alpha_K/(\alpha_L + \alpha_M + \alpha_N)$
KLX/KXY	abbreviation of P_{AKLX}/P_{AKXY}
L_1, L_2, L_3	L electron sub-shells
E0, E1, E2,...	electric monopole, dipole, quadrupole, etc.
M1, M2,...	magnetic dipole, quadrupole, etc.
δ	admixing of multipolarities: $\delta^2 = E(L+1)/M(L)$ (e.g., δ^2= E2/M1)
$\alpha_{K,\,L,\,M\,\ldots}$	K-, L-, M-shell etc. internal conversion coefficient
α_{total}	total internal conversion coefficient $(\alpha_{total} = \alpha_K + \alpha_L + \alpha_M + \cdots)$
α_π	internal-pair creation coefficient $\left(\alpha_\pi = N_e{}^{\pm}/N_\gamma\right)$
$N_e{}^{\pm}$	number of electron–positron pairs
N_γ	number of emitted photons
$\omega_{K,\,L,\,M\ldots}$	K-, L-, M-shell etc. fluorescence yields
a_K	K-Auger yield, $a_K = 1 - \omega_K$
$\bar{v}$	(1) fission: average number of neutrons emitted per neutron absorbed (2) antineutrino
$\left\|M_{0,\,1}\right\|^2$	nuclear matrix element
η	(1) combination of nuclear matrix elements (2) L_η X-ray emission

Decay processes, particles and quanta

α	alpha particle
β^-	electron (negatron) from beta decay
β^+	positron from electron-capture decay
ε (or EC)	electron capture
sf	spontaneous fission
IT	isomeric transition
β^-n	beta particle/delayed neutron
β^+p	beta particle (positron)/delayed proton
e(or e^-)	electron
e^+	positron (e.g., as created in pair production)
$e^{\pm}$	internal electron–positron pair
p	proton
n	neutron
v	neutrino
$\bar{v}$	antineutrino
γ	gamma ray
X	X-ray
X_K	KX-ray
X_L	LX-ray
ce	internal conversion electron
ce_K	internal conversion electron ejected from K shell
ce_L	internal conversion electron ejected from L shell
e_A	Auger electron
$e_{AK,\,L,\,M\,\ldots}$	K-, L-, M- etc. Auger electron
KLL, KLX, KXY...	KLL, KLX, KXY- etc Auger electron (X=M, N; Y=M, N)

Energies

E	energy
E_α	alpha-particle energy
E_β	beta-particle energy
E_γ	gamma-ray energy
E_{ph}	photon energy
$E_{\beta^-_{max}}$	maximum beta-particle energy (maximum negatron energy)
$E_{\beta^+_{max}}$	maximum positron-particle energy
$\bar{E}$	mean energy
$\bar{E}_\alpha$	mean alpha energy (related to all forms of heavy particle)
$\bar{E}_\beta$	mean beta energy (all forms of electron emission)
$\bar{E}_{\beta^-}$	mean beta-particle energy
$\bar{E}_{\beta^+}$	mean positron-particle energy
$\bar{E}_\gamma$	mean gamma energy (all types of electromagnetic radiation)
E_r (or E_{rl})	recoil energy

E_F	fission-fragment energy
E_l	energy of a nuclear level
$E_{K,L\ldots}$	binding energy of K-, L- etc. shell electron
E_n	neutron energy
E_p	proton energy
E_v	neutrino energy
E_e	monoenergetic electron energy
E_x	binding energy of electron in X shell (or sub-shell)
$E_{AK,L\ldots}$	K-, L- etc. Auger electron energy
E_{CK}	LLX-Auger electron energy (arises from Coster–Kronig transition)
$E_{ceK,L\ldots}$	K, L etc. conversion-electron energy
E_X	X-ray energy
$E_{XK,L\ldots}$	K, L etc X-ray energy
B_n	binding energy of neutron
q_x	neutrino energy after electron capture
$q_{K,L,M\ldots}$	neutrino energy after electron capture in the K-, L-, M- etc. shell
Q	total decay energy
Q_α	total alpha energy
Q_β or Q^-	total beta energy
Q_{EC} or Q^+	total electron-capture energy
Q_{sf}	spontaneous fission energy
$Q_{\beta\beta}$	total double-beta energy

Transition probabilities

P	emission probability
P_α	alpha-particle emission probability
P_β	beta-particle emission probability
P_{β^-}	electron emission probability (negatron emission probability)
P_{β^+}	positron emission probability
P_ε(or P_{EC})	electron-capture transition probability
P_{TP}	gamma transition probability $\left(P_{TP} = P_\gamma + P_{ce} + P_e{}^{\pm}\right)$
P_γ	gamma-ray emission probability
P_γ^{abs}	absolute gamma-ray emission probability
P_γ^{rel}	relative gamma-ray emission probability
$P_n(P_n{}^{total})$	delayed-neutron probability (total represents β^-n branching fraction)
P_p	proton emission probability
P_r	probability of recoil
P_F	probability of fission fragmentation
P_X	X-ray emission probability
$P_{XK,L,M\ldots}$	K, L, M, etc. X-ray emission probability
P_e	monoenergetic electron emission probability
P_{ce}	conversion-electron emission probability
$P_{ceK,L,M\ldots}$	K, L, M etc. conversion-electron emission probability
P_A	Auger electron emission probability
$P_{AK,L,M\ldots}$	K-, L-, M- etc. Auger electron emission probability
$P_{AKLL,KLX,KXY\ldots}$	KLL-, KLX-, KXY- etc. Auger electron emission probability
$P_e{}^{\pm}$	electron–positron pair emission probability
$P_{K,L,M\ldots}$	K-, L-, M- etc. shell capture probability for electron capture
P_{KK}	probability of double K-shell vacancy
f_{12}, f_{13}, f_{23}	probabilities of Coster–Kronig transitions
BF_i	branching fraction of ith decay mode

Units

s	second
min	minute
h	hour
d	day
yr	year (1 yr = 365.24220 d)
eV	electronvolt (keV, kilo-electronvolt; MeV, mega-electronvolt)
Bq	Becquerel (1 Bq = 1 disintegration per s)
ppm	parts per million (per 10^6)

Data uncertainties

Uncertainties in the data are presented in the format 1234(x), where x is the uncertainty in the last figure or figures quoted in the prime number. This uncertainty is generally expressed at the 1σ confidence level.

Examples:

1739(8) d means 1739 ± 8 d
4936.6(20) d means 4936.6 ± 2.0 d
$1.13(17) \times 10^6$ yr means $(1.13 \pm 0.17) \times 10^6$ yr
0.171(1) means 0.171 ± 0.001
0.01697(11) means 0.01697 ± 0.00011

References

Abdul-Hadi, A., 1998. Gamma-spectrum of ^{241}Am. J. Radioanal. Nucl. Chem. 231, 147–152.

Adsley, I., Backhouse, J.S., Nichols, A.L., Toole, J., 1998. U-238 decay chain: resolution of observed anomalies in the measured secular equilibrium between Th-234 and daughter Pa-234m. Appl. Radiat. Isot. 49, 1337–1344.

Ahmad, I., Phillips, W.R., 1995. Gamma-rays from fission fragments. Rep. Prog. Phys. 58, 1415–1463.

Attie, M.R.P., Koskinas, M.F., Dias, M.S., Fonseca, K.A., 1998. Absolute disintegration rate measurements of Ga-67. Appl. Radiat. Isot. 49, 1175–1177.

Audi, G., Wapstra, A.H., 1995. The 1995 update to the atomic mass evaluation. Nucl. Phys. A 595, 409–480.

Audi, G., Bersillon, O., Blachot, J., Wapstra, A.H., 1996. NUBASE: a database of nuclear and decay properties. Nucl. Instr. Meth. A 369, 511–515.

Audi, G., Bersillon, O., Blachot, J., Wapstra, A.H., 1997. The NUBASE evaluation of nuclear and decay properties. Nucl. Phys. A 624, 1–124.

Backhouse, J.S., Nichols, A.L., 1998. Assessment and evaluation of decay data for nuclear reactor applications. Appl. Radiat. Isot. 49, 1393–1396.

Balysh, A., Beck, M., Belyeav, S.T., Bensch, F., Bockholt, J., Demehin, A., Gurov, A., Heusser, G., Klapdor-Kleingrothaus, H.V., Kondratenko, I., Kotel'nikov, D., Lebedev, V.I., Maier, B., Müller, A., Petry, F., Peipke, A., Pronsky, A., Stecker, H., Völlinger, M., Zuber, K., 1994. Measurement of the $\beta\beta 2v$ decay of ^{76}Ge. Phys. Letters B 322, 176–181.

Band, I.M., Trzhaskovskaya, M.B., Listengarten, M.A., 1976. Internal conversion coefficients for atomic numbers $Z \leqslant 30$. At. Data Nucl. Data Tables 18, 433–457.

Banham, M.F., Jones, R., 1983. Gamma-ray-spectrometry measurements for actinide decay-scheme studies with particular reference to ^{231}Pa and ^{235}U. Int. J. Appl. Radiat. Isot. 34, 1225–1231.

Baranov, S.A., Shatinskii, V.M., Zelenkov, A.G., Pchelin, V.A., 1977. Study of γ radiation accompanying α decay of ^{235}U and β^- decay of ^{231}Th. Sov. J. Nucl. Phys. 26, 486–488.

Bé, M.M., Coursol, N., Duchemin, B., Lagoutine, F., Legrand, J., Debertin, K., Schönfeld, E., 1999a. Table de Radionucléides, Introduction. CEA, Saclay, ISBN 2-7272-0201-6.

Bé, M.M., Coursol, N., Duchemin, B., Lamé, J., Morillon, C., Piton, F., Browne, E., Chechev, V., Helmer, R.G., Schönfeld, E., 1999b. Table de Radionucléides. CEA, Saclay, ISBN 2-7272-0200-8.

Bé, M.M., Duchemin, B., Browne, E., Wu, S.-C., Chechev, V., Helmer, R.G., Schönfeld, E., 1999c. Table de Radionucléides, Comments on Evaluations. CEA, Saclay, ISBN 2-7272-0211-3.

Bé, M.M., Duchemin, B., Lamé, J., 1996. An interactive database for decay data. Nucl. Instr. Meth. A 369, 523–526.

Bhat, M.R., 1992. Evaluated Nuclear Structure Data File (ENSDF). In: Qaim, S.M. (Ed.), Proceedings of an International Conference on Nuclear Data for Science and Technology, Springer-Verlag, Berlin, pp. 817–821; also Nuclear Data Sheets, Academic Press Inc., New York.

Bjørnholm, S., Nielsen, O.B., 1963. The decay of the 1.14 min isomer of ^{234}Pa (UX_2). Nucl. Phys. 42, 642–659.

Bland, C.J., 1994. Alpha-particle emission probabilities for ^{241}Am. Nucl. Instr. Meth. A 339, 180–182.

Bland, C.J., Morel, J., Etcheverry, E., Lépy, M.C., 1992. Determination of ^{239}Pu and ^{241}Am LX-ray intensities using a Simplex method for fitting peaks. Nucl. Instr. Meth. A 312, 323–333.

Boboshin, I.N., Varlamov, V.V., Trukhanov, S.K., 1994. The relation IBM/PC nuclear structure and decay data base. In: Dickens, J.K. (Ed.), Proceedings of an International Conference on Nuclear Data for Science and Technology, Vol. 2, American Nuclear Society Inc., La Grange Park, pp. 759–761.

Bortels, G., Mouchel, D., Eykens, R., Garcia-Torano, E., Acena, M.L., Wiltshire, R.A.P., King, M., Fudge, A.J., Burger, P., 1990. Alpha-particle emission probabilities in the decay of ^{237}Np. Nucl. Instr. Meth. A 295, 199–206.

Bowles, N.E., Woods, S.A., Woods, D.H., Jerome, S.M., Woods, M.J., de Lavison, P., Lineham, S., Keightley, J., Poupaki, I., 1998. Standardisation of ^{153}Sm. Appl. Radiat. Isot. 49, 1345–1347.

Bradley, D.I., Stone, N.J., Rikovska, J., Novakova, D., Ferencei, J., 1986. Level spins and transition multipolarities in ^{56}Fe studied by nuclear orientation of ^{56}Co. J. Phys. G – Nucl. Phys. 12, 115–128.

Brady, M.C., England, T.R., 1989. Delayed neutron data and group parameters for 43 fissioning systems. Nucl. Sci. Engng. 103, 129–149.

Browne, E., Ahmad, I., Gregorich, K.E., Kreek, S.A., Lee, D.M., Hoffman, D.C., 1994. Electron-capture decay of ^{231}U. Nucl. Instr. Meth. A 339, 209–217.

Burcham, W.E., Jobes, M., 1995. Nuclear and Particle Physics. Longman Scientific & Technical, Harlow, ISBN 0-582-45088-8.

Camp, D.C., Meredith, G.L., 1971. The decays of ^{56}Co and ^{66}Ga and precise gamma-ray intensities. Nucl. Phys. A 166, 349–377.

Chauvenet, B., Morel, J., Legrand, J., 1983. An international intercomparision of photon emission rate measurements of X- and gamma rays emitted in the decay of ^{133}Ba. Int. J. Appl. Radiat. Isot. 34, 479–485.

Chu, S.Y.F., Firestone, R.B., Ekström, L.P., Nordberg, H., Dahlström, G., 1997. Electronic publication of nuclear data. In: Reffo, G., Ventura, A., Grandi, C. (Eds.), Proceedings of an International Conference on Nuclear Data for Science and Technology, Vol. 59, SIF, Bologna, pp. 894–898.

Cottingham, W.N., Greenwood, D.A., 1998. An Introduction to Nuclear Physics. Cambridge University Press, Cambridge, ISBN 0-521-31960-9.

Coursey, B.M., Hoppes, D.D., Schima, F.J., Unterweger, M.P., 1987. The standardisation of Samarium-153. Appl. Radiat. Isot. 38, 31–34.

Das, A., Ferbel, T., 1994. Introduction to Nuclear and Particle Physics. Wiley, New York, ISBN 0-471-59975-1.

Debertin, K., Helmer, R.G., 1988. Gamma- and X-Ray Spectrometry with Semiconductor Detectors. North-Holland, Amsterdam, ISBN 0-444-871071.

Decker, R., Wünsch, K.D., Wollnik, H., Koglin, E., Siegert, G., Jung, G., 1980. Präzise Q_β-wert-messungen mit einem intrinsic-germanium detektor an leichten, neutronenreichen spaltprodukten. Z. Phys. A 294, 35–49.

Denecke, B., 1987. Measurement of 56.5 keV gamma-ray emission probability in the decay of ^{241}Am, with a 4π-CsI(Tl)-sandwich spectrometer. Appl. Radiat. Isot. 38, 823–830.

Duchemin, B., Coursol, N., Bé, M.M., 1994. The re-evaluation of decay data for the U-238 chain. Nucl. Instr. Meth. A 339, 146–150.

Dunford, C.L., 1992. Evaluated Nuclear Data File ENDF/B-VI. In: Qaim, S.M. (Ed.), Proceedings of an International Conference on Nuclear Data for Science and Technology, Springer-Verlag, Berlin, pp. 788–792.

Dunford, C.L., 1994. Future directions in nuclear data dissemination. In: Dickens, J.K. (Ed.), Proceedings of an International Conference on Nuclear Data for Science and Technology, Vol. 1, American Nuclear Society Inc., La Grange Park, pp. 25–30.

Dunford, C.L., Burrows, T.W., 1999. Online nuclear data service. National Nuclear Data Centre, Brookhaven National Laboratory Report NNDC/ONL-99/3.

Egorov, A.G., Chechev, V.P., 1994. Measurements of absolute and relative emission probabilities of gamma- and X-rays and data evaluation in the decay of ^{155}Eu. Nucl. Instr. Meth. A 339, 248–252.

Endt, P.M., Alderliesten, C., 1994. Low-spin states of ^{66}Zn excited in the ^{66}Ga($\beta^+ + \varepsilon$)^{66}Zn decay. Nucl. Phys. A 575, 297–316.

Finck, Ph., Gruppelaar, H., Konieczny, M., Nordborg, C., Rowlands, J., 1997. The JEFF project and the JEFF-3 nuclear data library. In: Reffo, G., Ventura, A., Grandi, C. (Eds.), Proceedings of an International Conference on Nuclear Data for Science and Technology, Vol. 59, SIF, Bologna, pp. 1002–1007.

Firestone, R.B., Baglin, C.M., Chu, S.Y.F., 1998. Table of Isotopes, 8th Edition (1998 update with CD-ROM). Wiley, New York, ISBN 0-471-24699-9.

Firestone, R.B., Shirley, V.S., Baglin, C.M., Chu, S.Y.F., Zipkin, J., 1996. Table of Isotopes, 8th Edition, Vols I and II (includes CD-ROM). Wiley, New York, ISBN 0-471-14918-7.

Fogelberg, B., Mach, H., Gausemel, H., Omtvedt, J.P., Mezilev, K.A., 1998. New high spin isomers obtained in thermal fission. In: Fioni, G., Faust, H., Oberstedt, S., Hambsch, F.-J. (Eds.), Nuclear Fission and Fission-product Spectroscopy, Second International Workshop. AIP Conference Proceedings 447, American Institute of Physics, New York, pp. 191–195, ISBN 1-56396-823-1.

Forrest, R.A., 1994. Nuclear data for fusion calculations. In: Dickens, J.K. (Ed.), Proceedings of an International Conference on Nuclear Data for Science and Technology, Vol. 2, American Nuclear Society Inc., La Grange Park, pp. 854–858.

Forrest, R.A., Mann, F.M., 1997. FENDL/D-2.0 decay data library for fusion applications. In: Pashchenko, A.B., Wienke, H. (Eds.), Summary Documentation. IAEA Report IAEA-NDS-178, Vienna; also IAEAND Website.

Forrest, R.A., Sublet, J.-Ch., 1998. The European Activation File EAF-99 decay data library. UK Atomic Energy Authority Report UKAEA FUS 409.

Garcia-Torano, E., 1998. Alpha-particle emission probabilities in the decay of ^{244}Cm. Appl. Radiat. Isot. 49, 1325–1328.

Garcia-Torano, E., 2000. Alpha-particle emission probabilities in the decay of ^{238}U. Appl. Radiat. Isot. 52, 591–594.

Garcia-Torano, E., Acena, M.L., Bortels, G., Mouchel, D., 1992. Alpha-particle emission probabilities in the decay of ^{243}Am. Nucl. Instr. Meth. A 312, 317–322.

Genoux-Lubain, A., Ardisson, G., 1978a. Le rayonnement γ de basse énergie qui accompagne la décroissance α de ^{241}Am. Radiochem. Radioanal. Lett. 33, 59–66.

Genoux-Lubain, A., Ardisson, G., 1978b. Nouvelles transitions électromagnétiques dans le noyau ^{237}Np formées par décroissance α de ^{241}Am. CR Acad. Sci. Paris B 287, 13–16.

Gilmore, G., Hemingway, J.D., 1995. Practical Gamma-ray Spectroscopy. Wiley, Chichester, ISBN 0-471-95150-1.

Glover, K.M., 1984. Alpha-particle spectrometry and its applications. Appl. Radiat. Isot. 35, 239–250.

Godart, J., Gizon, A., 1973. Niveaux de ^{234}Pa atteints par la desintegration de ^{234}Th. Nucl. Phys. A 217, 159–176.

Grau Carles, A., Rodriguez Barquero, L., Jimenez de Mingo, A., 1998. ^{125}Sb to ^{125m}Te branching ratio. Appl. Radiat. Isot. 49, 1377–1381.

Greenwood, R.C., Caffrey, A.J., 1985. Delayed-neutron energy spectra of $^{93\text{-}97}$Rb and $^{143\text{-}145}$Cs. Nucl. Sci. Engng. 91, 305–323.

Greenwood, R.C., Watts, K.D., 1997. Delayed neutron energy spectra of ^{87}Br, ^{88}Br, ^{89}Br, ^{90}Br, ^{137}I, ^{138}I, ^{139}I and ^{136}Te. Nucl. Sci. Engng. 126, 324–332.

Greenwood, R.C., Helmer, R.G., Putnam, M.H., Watts, K.D., 1997. Measurement of β^- decay intensity distributions of several fission-product isotopes using a total absorption γ-ray spectrometer. Nucl. Instr. Meth. A 390, 95–154.

Greenwood, R.C., Putnam, M.H., Watts, K.D., 1996. Ground-state β^- branching intensities of several fission-product isotopes measured using a total absorption γ-ray spectrometer. Nucl. Instr. Meth. A 378, 312–320.

Grennberg, B., Rytz, A., 1971. Absolute measurements of α-ray energies. Metrologia 7, 65–77.

Gunnink, R., Tinney, J.F., 1971. Analysis of fuel rods by gamma-ray spectroscopy. Lawrence Radiation Laboratory Report UCRL-51086.

Haas, P., Gartenmann, P., Golser, R., Kutschera, W., Suter, M., Synal, H.-A., Wagner, M.J.M., Wild, E., Winkler, G., 1996. A new half-life measurement of the long-lived fission product ^{126}Sn. Nucl. Instr. Meth. B 114, 131–137; Erratum (1996), Nucl. Instr. Meth. B 117, 474.

Hager, R.S., Seltzer, E.C., 1968. Internal conversion tables, Part 1: K-, L-, M-shell conversion coefficients for $Z = 30$ to $Z = 103$. Nucl. Data Tables A 4, 1–235.

Hamilton, J.H., Ramayya, A.V., Zhu, S.J., Ter-Akopian, G.M., Organessian, Yu.Ts., Cole, J.D., Rasmussen, J.O., Stoyer, M.A., 1995. New insights from studies of spontaneous fission with large detector arrays. Prog. Part. Nucl. Phys. 35, 635–704.

Hammed, M.A., Lowles, I.M., MacMahon, T.D., 1992. Decay scheme data for ^{154}Eu, ^{198}Au and ^{239}Np. Nucl. Instr. Meth. A 312, 308–316.

Hautala, M., Anttila, A., Keinonen, J., 1978. Relative intensities of gamma rays from ^{56}Co standard source. Nucl. Instr. Meth. 150, 599–601.

Heath, R.L., 1974. Gamma-ray spectrum catalogue. AEC Report ANC-1000-2.

Helmer, R.G., 1996. Radioisotopes. In: Kirk-Othmer Encyclopedia of Chemical Technology, 4th Edition, Vol. 20, Wiley, New York, pp. 871–906, ISBN 0-471-52689-4.

Helmer, R.G., Gehrke, R.J., Davidson, J.R., Mandler, J.W., 2000. Scientists, spectrometry and gamma-ray spectrum catalogues, 1957–2007. J. Radioanal. Nucl. Chem. 243, 109–117.

Helmer, R.G., Greenwood, R.C., Watts, K.D., Putnam, M.H., 1994a. Beta-particle feeding distributions for $^{138\text{-}141}$Cs from total absorption gamma-ray spectrometer (TAGS). Nucl. Instr. Meth. A 339, 189–199.

Helmer, R.G., Putnam, M.H., Greenwood, R.C., Willmes, H., 1994b. Methodology for the measurement of β^- decay intensity distributions from the analysis of total absorption γ-ray spectra. Nucl. Instr. Meth. A 351, 406–422; Erratum (1995), Nucl. Instr. Meth. A 361, 628.

Helmer, R.G., Reich, C.W., 1984. Emission probabilities and energies of γ-ray transitions from the decay of ^{235}U. Int. J. Appl. Radiat. Isot. 35, 783–786.

Helmer, R.G., Van Assche, P.H.M., van der Leun, C., 1979. Recommended standards for gamma-ray energy calibration (1979). At. Data Nucl. Data Tables 24, 39–48.

Helmer, R.G., van der Leun, C., 2000. Recommended standards for γ-ray energy calibration (1999). Nucl. Instr. Meth. A 450, 35–70.

Herman, M., Nichols, A.L., 1999. Update of X- and γ-ray decay data standards for detector calibration and other applications. IAEA Report INDC(NDS)-403, Vienna.

Heyde, K., 1999. Basic Ideas and Concepts in Nuclear Physics, an Introductory Approach, 2nd Edition. Institute of Physics Publishing, Bristol, ISBN 0-7503-0535-5.

Hodgson, P.E., Gadioli, E., Gadioli Erba, E., 1997. Introductory Nuclear Physics. Oxford University Press, Oxford, ISBN 0-19-851897-8.

Hoff, P., 1981. The population of excited states in residual nuclei via delayed neutrons. Nucl. Phys. A 359, 9–35.

Hourany, E., Plonski, I.H., Poenaru, D.N., 1997. Track detectors and SOLENO applied to cluster radioactivities. In: Poenaru, D.N., Greiner, W. (Eds.), Experimental Techniques in Nuclear Physics, Walter de Gruyter, Berlin, pp. 117–135, ISBN 3-11-014467-0.

IAEA, 1976. Transactinium isotope nuclear data. Proceedings of IAEA Advisory Group Meeting, Karlsruhe, IAEA-TECDOC-186, Vienna.

IAEA, 1979. Transactinium isotope nuclear data–1979. Proceedings of Second IAEA Advisory Group Meeting, Cadarache, IAEA-TECDOC-232, Vienna.

IAEA, 1986. Decay data of the transactinium nuclides. Technical Reports Series No. 261, Vienna.

IAEA, 1991. X-ray and gamma-ray standards for detector calibration. IAEA-TECDOC-619, Vienna.

Iafigliola, R., Chatterjee, M., Dautet, H., Lee, J.K.P., 1983. Precise Q_β measurements for $A = 91$ to 93 mass chains. Can. J. Chem. 61, 694–696.

Ikuta, T., Taniguchi, A., Yomamoto, H., Kawade, K., Kawase, Y., 1994. Q_β measurements of neutron-rich isotopes in the mass region $147 \leqslant A \leqslant 152$. In: Dickens, J.K. (Ed.), Proceedings of an International Conference on Nuclear Data for Science and Technology, Vol. 1, American Nuclear Society Inc., La Grange Park, pp. 331–333.

Jagam, P., Simpson, J.J., 1992. Intensity of the 1001 keV γ-ray in the decay of ^{234m}Pa. J. Radioanal. Nucl. Chem. Lett. 166, 393–399.

JEF-2.2 radioactive decay data, 1994. JEF Report 13, NEA-OECD, Issy-les-Moulineaux.

Jiang Songsheng, Guo Jingru, Jiang Shan, Li Chunsheng, Cui Anzhi, He Ming, Wu Shaoyong, Li Shilin, 1997. Determination of the half-life of ^{79}Se with the accelerator mass spectrometry technique. Nucl. Instr. Meth. B 123, 405–409.

Karmalitsyn, N.I., Sazonova, T.E., Zanevsky, A.V., Sepman, S.V., 1998. Standardization and half-life measurement of ^{55}Fe. Appl. Radiat. Isot. 49, 1363–1366.

Katakura, J., England, T.R., 1991. Augmentation of ENDF/B fission product gamma-ray spectra by calculated spectra. Los Alamos National Laboratory Report LA-12125-MS.

Kautzsch, T., Walters, W.B., Kratz, K.-L., 1998. Laser isotope and isomer separation of neutron-rich Ag isotopes. In: Fioni, G., Faust, H., Oberstedt, S., Hambsch, F.-J. (Eds.), Nuclear Fission and Fission-product Spectroscopy, Second International Workshop. AIP Conference Proceedings 447, American Institute of Physics, New York, pp. 183–190, ISBN 1-56396-823-1.

Kinsey, R.R., 1996. The NuDat program for nuclear data on the web. National Nuclear Data Centre, Brookhaven National Laboratory Report, Version 2.5; also IAEAND and NNDC Websites.

Kinsey, R.R., McLane, V., Burrows, T.W., 1994. Nuclear data services in the 90s: responding to expanding technologies and shrinking budgets. In: Dickens, J.K. (Eds.), Proceedings of an International Conference on Nuclear Data for Science and Technology, Vol. 2, American Nuclear Society Inc., La Grange Park, pp. 745–747.

Knoll, G.F., 2000. Radiation Detection and Measurement, 3rd Edition. Wiley, New York, ISBN 0-471-07338-5.

Konieczny, M., Potet, B., Rockey, J., 1994. A PC program for displaying data from the Joint Evaluated File (JEF) library. In: Dickens, J.K. (Ed.), Proceedings of an International Conference on Nuclear Data for Science and Technology, Vol. 2, American Nuclear Society Inc., La Grange Park, pp. 754–758.

Konieczny, M., Weaver, D.R., Hale, D., Baynham, I., Tagzira, H., Weaver, R.A., 1997. A PC program for viewing evaluated and experimental data. In: Reffo, G., Ventura, A., Grandi, C. (Eds.), Proceedings of an International Conference on Nuclear Data for Science and Technology, Vol. 59, SIF, Bologna, pp. 1063–1065.

Konstantinov, A.A., Sazonova, T.E., Sepman, S.V., Zanevsky, A.V., Karmalitsyn, N.I., 1994. Determination of X-ray and gamma-ray emission probabilities of ^{51}Cr and ^{88}Y. Nucl. Instr. Meth. A 339, 200–202.

Koua Aka, A., Ardisson, G., Barci, V., El Samad, O., Trubert, D., Ahmad, I., 1996. Reinvestigation of the α-decays of ^{249}Cf and ^{233}U. Nucl. Instr. Meth. A 369, 477–485.

Krane, K.S., 1988. Introductory Nuclear Physics. Wiley, New York, ISBN 0-471-80553-X.

Kratz, K.-L., Rudolph, W., Ohm, H., Franz, H., Zendel, M., Herrmann, G., Prussin, S.G., Nuh, F.M., Shihab-Eldin, A.A., Slaughter, D.R., Halverson, W., Klapdor, H.V., 1979. Investigation of beta strength functions by neutron and gamma-ray spectroscopy, I: the decay of ^{87}Br, ^{137}I, ^{85}As and ^{135}Sb. Nucl. Phys. A 317, 335–362.

Kratz, K.-L., Schröder, A., Ohm, H., Zendel, M., Gabelmann, H., Ziegert, W., Peuser, P., Jung, G., Pfeiffer, B., Wünsch, K.D., Wollnik, H., Ristori, C., Crancon, J., 1982. Beta-delayed neutron emission from $^{93\text{-}100}$Rb to excited states in the residual Sr iotopes. Z. Phys. A – Atoms and Nuclei 306, 239–257.

Kratz, K.-L., Ohm, H., Schröder, A., Gabelmann, H., Ziegert, W., Pfeiffer, B., Jung, G., Monnand, E., Pinston, J.A., Schussler, F., Crawford, G.I., Prussin, S.G., de Oliveira, Z.M., 1983. The beta-decay of ^{95}Rb and ^{97}Rb. Z. Phys. A – Atoms and Nuclei 312, 43–57.

Lagoutine, F., Coursol, N., Legrand, J., 1982–1987. Table de Radionucléides. LMRI, CEA, Saclay, ISBN 2-7272-0078-1.

Lemmel, H.D., Schwerer, O., 1998. Index of nuclear data libraries from the IAEA Nuclear Data Section. IAEA Report IAEA-NDS-7, Vienna; also IAEAND Website.

Lépy, M.C., Debertin, K., 1994. Determination of ^{239}Pu and ^{240}Pu LX-ray emission probabilities. Nucl. Instr. Meth. A 339, 218–225.

Lhersonneau, G., Dendooven, P., Hankonen, S., Honkanen, A., Huhta, M., Oinonen, M., Penttilä, H., Peräjärvi, K., Wang, J.C., Äystö, J., 1998. Studies of neutron-rich nuclei at the JYFL-IGISOL. In: Fioni, G., Faust, H., Oberstedt, S., Hambsch, F.-J. (Eds.), Nuclear Fission and Fission-product Spectroscopy, Second International Workshop. AIP Conference Proceedings 447, American Institute of Physics, New York, pp. 167–174, ISBN 1-56396-823-1.

Lhersonneau, G., Honkanen, A., Huhta, M., Jauho, P.P., Jokinen, A., Leino, M., Oinonen, M., Ollikainen, E., Parmonen, J.M., Äystö, J., 1994. Beta decay of very neutron-rich ^{110}Mo studied at the new IGISOL facility. Z. Phys. A 350, 97–98.

Li Chunsheng, Guo Jingru, Li Daming, 1997. A procedure for the separation of ^{79}Se from fission products and application to the determination of the ^{79}Se half-life. J. Radioanal. Nucl. Chem. 220, 69–71.

Lin, W.-J., Harbottle, G., 1991. Gamma-ray emission intensities of ^{226}Ra in equilibrium with its daughter products. J. Radioanal. Nucl. Chem. Lett. 153, 137–149.

Lin, W.-J., Harbottle, G., 1992. Gamma-ray emission intensities of the ^{232}Th chain in secular equilibrium, of ^{235}U and the progeny of ^{238}U. J. Radioanal. Nucl. Chem. 157, 367–372.

Lister, C.J., 2000. How far from stability can we go using Gammasphere and the FMA? J. Res. Natl. Inst. Stand. Technol. 105, 137–140.

Longworth, G., Carpenter, B., Bull, R., Toole, J., Nichols, A. L., 1998. The Radiochemical Manual. AEA Technology plc, Harwell, ISBN 0-7058-1768-7.

Lorenz, A., 1985. Gamma-ray standards for detector calibration, Summary report of a consultants' meeting held at the Centre d'Etudes Nucléaires de Grenoble, France. IAEA Report INDC(NDS)–171, Vienna.

Los Arcos, J.M., Bailador, A., Gonzalez, A., Gonzalez, C., Gorostiza, C., Ortiz, F., Sanchez, E., Shaw, M., Williart, A., 2000. The Spanish national reference database for ionizing radiations (BANDRRI). Appl. Radiat. Isot. 52, 335–340.

Lowles, I.M., MacMahon, T.D., Banham, M.F., Fudge, A.J., Wiltshire, R.A.P., 1990. Reconciliation of ^{237}Np decay scheme data. Nucl. Instr. Meth. A 286, 556–562.

Luca, A., Etcheverry, M., Morel, J., 2000. Emission probabilities of the main γ-rays of ^{237}Np in equilibrium with ^{233}Pa. Appl. Radiat. Isot. 52, 481–486.

Magill, J., 1999. Nuclides 2000: an Electronic Chart of the Nuclides - User's Guide. EUR 18737 EN, Office for Official Publications of the European Communities, Luxembourg, ISBN 92-828-6512-6.

Mann, W.B., Ayres, R.L., Garfinkel, S.B., 1980. Radioactivity and its Measurement, 2nd Edition. Pergamon Press, Oxford, ISBN 0-08-025028-9.

Mikheev, V.L., Tretyakova, S.P., 1997. Experimental data on the cluster decay of heavy nuclei and the correlation between the probabilities of alpha decay, cluster decay and spontaneous fission. In: Reffo, G., Ventura, A., Grandi, C. (Eds.), Proceedings of an International Conference on Nuclear Data for Science and Technology, Vol. 59, SIF, Bologna, pp. 826–828.

Miyahara, H., Matumoto, H., Mori, C., Takeuchi, N., Genka, T., 1994. Determination of gamma-ray emission probabilities for ^{75}Se, ^{166m}Ho and ^{192}Ir by a self-consistent method. Nucl. Instr. Meth. A 339, 203–208.

Miyahara, H., Nagata, H., Furusawa, T., Murakami, N., Mori, C., Takeuchi, N., Genka, T., 1998. Gamma-ray emission probabilities of ^{182}Ta. Appl. Radiat. Isot. 49, 1383–1386.

Miyahara, H., Wurdiyanto, G., Nagata, H., Yoshida, A., Yanagida, K., Mori, C., 2000. Precise measurements of the gamma-ray emission probabilities of ^{186}Re and ^{188}Re. Appl. Radiat. Isot. 52, 573–579.

Miyahara, H., Yoshida, A., Wurdiyanto, G., Hara, K., Yanagida, K., Mori, C., 1996. Precise measurement of the gamma-ray emission probabilities of ^{38}Cl. Nucl. Instr. Meth. A 369, 494–497.

Momeni, M.H., 1982. Analyses of uranium and actinium gamma spectra: an application to the measurements of environmental contamination. Nucl. Instr. Meth. 193, 185–190.

Morel, J., Etcheverry, M., Plagnard, J., 2000. Results from the EUROMET action 410 concerning the decay data of ^{169}Yb. Appl. Radiat. Isot. 52, 455–466.

Moss, C.E., 1986. Gamma-ray line intensities for depleted uranium. Radiat. Eff. 94, 81–84.

National Nuclear Data Centre, 1987. ENSDF: the evaluated nuclear structure data file. Brookhaven National Laboratory Report BNL-NCS-51655.

Nichols, A.L., 1990. X- and gamma-ray standards for detector efficiency calibration. Nucl. Instr. Meth. A 286, 467–473.

Nichols, A.L., 1991. Heavy element and actinide decay data: UKHEDD-2 data files. AEA Technology Report AEA-RS-5219.

Nichols, A.L., 1993. Activation product decay data: UKPADD-2 data files. AEA Technology Report AEA-RS-5449.

Nichols, A.L., 1996. Tables of alpha-particle emitters: energies and emission probabilities. In: Poenaru, D.N., Greiner, W. (Eds.), Handbook of Nuclear Properties. Clarendon Press, Oxford, pp. 237–247.

Nichols, A.L., Dean, C.J., Neill, A.P., 1999a. Extension and maintenance of evaluated decay data files: UKPADD-6. AEA Technology Report AEAT-5226.

Nichols, A.L., Dean, C.J., Neill, A.P., Perry, R.J., 1999b. UKPADD-6: evaluated decay data library, March 1999. AEA Technology Report AEAT-5281.

Nichols, A.L., Herman, M., 1998. Report on consultants' meeting on preparation of the proposal for a co-ordinated research project to update X- and γ-ray decay data standards for detector calibration. IAEA Report INDC(NDS)–378, Vienna.

Nolan, P.J., Beck, F.A., Fossan, D.B., 1994. Large arrays of escape-suppressed gamma-ray detectors. Ann. Rev. Nucl. Part. Sci. 45, 561–607.

Nordborg, C., Salvatores, M., 1994. Status of the JEF evaluated data library. In: Dickens, J.K. (Ed.), Proceedings of an International Conference on Nuclear Data for Science and Technology, Vol. 2, American Nuclear Society Inc., La Grange Park, pp. 680–684.

Nordborg, C., Gruppelaar, H., Salvatores, M., 1992. Status of the JEF and EFF projects. In: Qaim, S.M. (Ed.), Proceedings of an International Conference on Nuclear Data for Science and Technology, Springer-Verlag, Berlin, pp. 782–787.

Nordborg, C., McLane, V., Schwerer, O., Manokhin, V.N., 1997. The Nuclear Data Centres network. In: Reffo, G., Ventura, A., Grandi, C. (Eds.), Proceedings of an International Conference on Nuclear Data for Science and Technology, Vol. 59, SIF, Bologna, pp. 1069–1073.

Nuh, F.M.G., 1975. Investigation of delayed-neutron emission through gamma-ray and neutron spectroscopy. Ph.D. Thesis, Department of Nuclear Engineering, University of California, Berkeley.

Nuh, F.M., Slaughter, D.R., Prussin, S.G., Ohm, H., Rudolph, W., Kratz, K.-L., 1977. Delayed neutrons and high-energy γ-rays from decay of ^{87}Br. Nucl. Phys. A 293, 410–424.

Oberli, F., Gartenmann, P., Meier, M., Kutschera, W., Suter, M., Winkler, G., 1999. The half-life of ^{126}Sn refined by thermal ionization mass spectrometry measurements. Int. J. Mass Spec. 184, 145–152.

Ohm, H., Zendel, M., Prussin, S.G., Rudolph, W., Schröder, A., Kratz, K.-L., Ristori, C., Pinston, J.A., Monnand, E., Schussler, F., Zirnheld, J.P., 1980. Beta-delayed neutrons and high-energy gamma rays from decay of ^{137}I. Z. Phys. A – Atoms and Nuclei 296, 23–33.

Olson, D.G., 1983. Gamma intensities for ^{226}Ra and daughters, and ^{235}U. Nucl. Instr. Meth. 206, 313–316.

Pearcey, J., Woods, S.A., Christmas, P., 1990. The internal conversion electron spectrum at very low energy, following ^{237}Np decay. Nucl. Instr. Meth. A 294, 516–522.

Penttilä, H., Dendooven, P., Honkanen, A., Huhta, M., Jauho, P.P., Jokinen, A., Lhersonneau, G., Oinonen, M., Parmonen, J.-M., Peräjärvi, K., Äystö, J., 1997. Status report of the Jyväskylä ion guide isotope separator on-line facility. Nucl. Instr. Meth. B 126, 213–217.

Phelps, M.E., Sarantites, D.G., Winn, W.G., 1970. Decay of ^{56}Co and ^{66}Ga: energy and intensity standardization. Nucl. Phys. A 149, 647–672.

Poenaru, D.N., Greiner, W., 1997. Experimental Techniques in Nuclear Physics. Walter de Gruyter, Berlin, ISBN 3-11-014467-0.

Poenaru, D.N., Greiner, W., Gherghescu, R.A., 1997. Cluster radioactivity and cold fission. In: Reffo, G., Ventura, A., Grandi, C. (Eds.), Proceedings of an International Conference on Nuclear Data for Science and Technology, Vol. 59, SIF, Bologna, pp. 70–76.

Povh, B., Rith, K., Scholz, C., Zetsche, F., 1999. Particles and Nuclei, an Introduction to the Physical Concepts, 2nd Edition. Springer-Verlag, Berlin and Heidelberg, ISBN 3-540-66115-8.

Przewloka, M., Przewloka, A., Wächter, P., Wollnik, H., 1992a. Measurements of β-endpoint-energies using a magnetic electron separator. Z. Phys. A – Hadrons and Nuclei 342, 23–26.

Przewloka, M., Przewloka, A., Wächter, P., Wollnik, H., 1992b. New Q_{β}-values of $^{139\text{-}146}$Cs. Z. Phys. A – Hadrons and Nuclei 342, 27–29.

Rajput, M.U., MacMahon, T.D., 1992. Techniques for evaluating discrepant data. Nucl. Instr. Meth. A 312, 289–295.

Raman, S., Fogelberg, B., Harvey, J.A., Macklin, R.L., Stelson, P.H., Schröder, A., Kratz, K.-L., 1983. Overlapping β decay and resonance neutron spectroscopy of levels in ^{87}Kr. Phys. Rev. C28, 602-622; Erratum (1984), Phys. Rev. C29, 344.

Razdolescu, A.C., Grigorescu, E.L., Sahagia, M., Luca, A., Ivan, C., 2000. Standardisation of ^{169}Yb by the $4\pi\beta$–γ method. Appl. Radiat. Isot. 52, 505–507.

Rehfield, D.M., 1978. An iterative technique for the analysis of detector-distorted data and its application to beta-ray spectroscopy. Nucl. Instr. Meth. 157, 351–364.

Reus, U., Westmeier, W., 1983. Catalog of gamma rays from radioactive decay. At. Data Nucl. Data Tables 29, 1–406.

Rösel, F., Fries, H.M., Alder, K., Pauli, H.C., 1978. Internal conversion coefficients for all atomic shells: ICC values for $Z=30-67$ and $Z=68-104$. At. Data Nucl. Data Tables 21, 91–289 and 291–514.

Roteta, M., Garcia-Torano, E., 1998. Determination of multipolarities and mixing ratios of some γ transitions following ^{125}Sb decay by γ–γ angular correlation. Appl. Radiat. Isot. 49, 1349–1352.

Rudstam, G., England, T.R., 1990. Test of pre-ENDF/B-VI decay data and fission yields. Los Alamos National Laboratory Report LA-11909-MS.

Rudstam, G., Johansson, P.I., Tengblad, O., Aagaard, P., Eriksen, J., 1990. Beta and gamma spectra of short-lived fission products. At. Data Nucl. Data Tables 45, 239–320.

Rudstam, G., Aleklett, K., Sihver, L., 1993. Delayed-neutron branching ratios of precursors in the fission product region. At. Data Nucl. Data Tables 53, 1–22.

Rytz, A., 1991. Recommended energy and intensity values of alpha particles from radioactive decay. At. Data Nucl. Data Tables 47, 205–239.

Salem, S.I., Panossian, S.L., Kause, R.A., 1974. Experimental K and L relative x-ray emission rates. At. Data Nucl. Data Tables 14, 91–109.

Sardari, D., MacMahon, T.D., Holloway, S.P., 1996. ^{239}U and ^{243}Am decay data. Nucl. Instr. Meth. A 369, 486–490.

Sazonova, T.E., Sepman, S.V., Karmalitsyn, N.I., Zanevsky, A.V., Shilnikova, T.I., Gabitov, R.M., 2000. Standardisation of ^{169}Yb and γ-ray emission probability data. Appl. Radiat. Isot. 52, 499–504.

Schönfeld, E., Janßen, H., Schötzig, U., Günther, E., Schrader, H., 1994. Standardisation and decay data of ^{186}Re. Nucl. Instr. Meth. A 339, 174–179.

Schötzig, U., Debertin, K., 1983. Photon emission probabilities per decay of ^{226}Ra and ^{232}Th in equilibrium with their daughter products. Int. J. Appl. Radiat. Isot. 34, 533–538.

Schötzig, U., Schrader, H., Debertin, K., 1992. Precision measurements of radioactive decay data. In: Qaim, S.M. (Ed.), Proceedings of an International Conference on Nuclear Data for Science and Technology, Springer-Verlag, Berlin, pp. 562–564.

Schötzig, U., Schönfeld, E., Janßen, H., 2000. Standardisation and photon emission probabilities in the decay of ^{237}Np/^{233}Pa. Appl. Radiat. Isot. 52, 883–889.

Scott, H.L., Marlow, K.W., 1990. Gamma-ray emission probabilities of the daughters of ^{238}U. Nucl. Instr. Meth. A 286, 549–555.

Shalev, S., Rudstam, G., 1977. Energy spectra of delayed neutrons from separated fission products, III: the precursors ^{88}Br, ^{90}Br, ^{138}I, ^{140}I, ^{142}(Xe + Cs) and ^{144}Cs. Nucl. Phys. A 275, 76–92.

Shannon, J.A., Phillips, W.R., Varley, B.J., Ahmad, I., Morss, L.R., 1994. Coincidence measurements following the alpha decay of ^{245}Cm. Nucl. Instr. Meth. A 339, 183–188.

Sibbens, G., Denecke, B., 2000. Determination of absolute alpha-particle emission probabilities of ^{237}Np. Appl. Radiat. Isot. 52, 467–470.

Siegert, H., Schrader, H., Schötzig, U., 1998. Half-life measurements of europium radionuclides and the long-term stability of detectors. Appl. Radiat. Isot. 49, 1397–1401.

Siemon, K., Esterlund, R.A., van Aarle, J., Knaack, M., Westmeier, W., Patzelt, P., 1992. A new measurement of the gamma-ray intensities of ^{234m}Pa accompanying the decay of ^{238}U. Appl. Radiat. Isot. 43, 873–880.

Simpson, B.R.S., Ntsoane, T.P., 2000. Decay scheme of ^{67}Ga. Appl. Radiat. Isot. 52, 551–556.

Singh, B., Rodriguez, J.L., Wong, S.S.M., Tuli, J.K., 1998. Review of logft values in β decay. Nucl. Data Sheets 84, 487–563.

Smith, D., Woods, D.H., Woods, S.A., Makepeace, J.L., Mercer, R.A., Downey, C.W.A., 1992. Standardisation of ^{125}Sb and ^{154}Eu and measurement of absolute gamma-ray emission probabilities. Nucl. Instr. Meth. A 312, 353–358.

Stewart, N.M., Shaban, A.M., 1980. Low lying energy levels of ^{56}Fe from γ–γ coincidences. Z. Phys. A – Atoms and Nuclei 296, 165–171.

Stippler, R., Münnich, F., Schrader, H., Bocquet, J.P., Asghar, M., Siegert, G., Decker, R., Pfeiffer, B., Wollnik, H., Monnand, E., Schussler, F., 1978. Experimental beta-decay energies of short-lived light fission products. Z. Phys. A 284, 95–104.

Su Zongdi, Ge Zhigang, Zhang Limin, Yu Ziqiang, Zuo Yixin, Huang Zhongfu, Liu Jianfeng, 1994. Chinese evaluated nuclear parameter library (CENPL). In: Dickens J.K. (Ed.), Proceedings of an International Conference on Nuclear Data for Science and Technology, Vol. 2, American Nuclear Society Inc., La Grange Park, pp. 712–714.

Su Zongdi, Ge Zhigang, Sun Zhengjun, Zhang Limin, Huang Zhongfu, Dong Liaoyuan, Liu Jianfeng, Zuo Yixin, Yu Ziqiang, Zhang Xiaocheng, Chen Zhenpeng, Ma Gonggui, 1997. Chinese evaluated nuclear parameter library (CENPL) and studies on corresponding model parameters. In: Reffo, G., Ventura, A., Grandi, C. (Eds.), Proceedings of an International Conference on Nuclear Data for Science and Technology, Vol. 59, SIF, Bologna, pp. 907–909.

Sutton, G.A., Napier, S.T., John, M., Taylor, A., 1993. Uranium-238 decay chain data. Sci. Tot. Environ. 130/131, 393–401.

Takahashi, K., Yamada, M., Kondoh, T., 1973. Beta-decay half-lives calculated on the gross theory. At. Data Nucl. Data Tables 12, 101–142.

Tasaka, K., Katakura, J., Ihara, H., Yoshida, T., Iijima S., Nakasima, R., Nakagawa, T., Takano, H., 1990. JNDC nuclear data library of fission products - second version. Japan Atomic Energy Research Institute Report JAERI 1320.

Teoh, W., Connor, R.D., Betts, R.H., 1974. The decay of ^{235}U. Nucl. Phys. A 228, 432–444.

Tepel, J.W., Müller, H.-W., 1990. GAMCAT - a personal computer database on alpha particles and gamma rays from radioactive decay. Nucl. Instr. Meth. A 286, 443–446.

Usman, K., MacMahon, T.D., 2000. Determination of the half-life of ^{233}Pa. Appl. Radiat. Isot. 52, 585–589.

Usman, K., MacMahon, T.D., Kafala, S.I., 1998. Determination of the half-life of ^{233}Th. Appl. Radiat. Isot. 49, 1329–1335.

Vaninbroukx, R., Denecke, B., 1982. Determination of gamma-ray emission probabilities in the decay of ^{235}U and ^{231}Th. Nucl. Instr. Meth. 193, 191–196.

Vaninbroukx, R., Bortels, G., Denecke, B., 1984. Determination of photon-emission probabilities in the decay of ^{237}Np and its daughter ^{233}Pa. Int. J. Appl. Radiat. Isot. 35, 905–906.

Vanó, E., Gaeta, R., Gonzalez, L., Liang, C.F., 1975. Étude des niveaux excités du ^{231}Th par la désintégration α du ^{235}U. Nucl. Phys. A 251, 225–245.

Wang, G., Warburton, E.K., Alburger, D.E., 1988. Precision energy determinations of gamma transitions from ^{56}Co decay. Nucl. Instr. Meth. A 272, 791–799.

Warner, D.D., 2000. Nuclear structure - the future with radioactive beams. J. Res. Natl. Inst. Stand. Technol. 105, 33–42.

Westmeier, W., Merklin, A., 1985. Catalog of alpha particles from radioactive decay. Physik Daten/Physics Data, 29-1, Fachinformationszentrum Energie, Physik-Mathematik GmbH, Karlsruhe.

Woods, D.H., Ciocanel, M., Husband, L.J., Keightley, J.D., de Lavison, P., Lineham, S., Woods, M.J., Woods, S.A., 2000. Standardisation and decay data of ^{186}Re. Appl. Radiat. Isot. 52, 581–584.

Woods, S.A., Christmas, P., Cross, P., Judge, S.M., Gelletly, W., 1988. Decay studies of ^{237}Np with an iron-free $\pi\sqrt{2}$ double-focusing, β-ray spectrometer of improved efficiency. Nucl. Instr. Meth. A 264, 333–356.

Woods, S.A., Woods, D.H., Woods, M.J., Jerome, S.M., Burke, M., Bowles, N.E., Lucas, S.E.M., Paton Walsh, C., 1996. Standardisation and measurement of the decay scheme data of ^{243}Am and ^{239}Np. Nucl. Instr. Meth. A 369, 472–476.

Woods, S.A., Woods, D.H., de Lavison, P., Jerome, S.M., Makepeace, J.L., Woods, M.J., Husband, L.J., Lineham, S., 2000. Standardisation and measurement of the decay scheme data of ^{237}Np. Appl. Radiat. Isot. 52, 475–479.

Wünsch, K.D., Decker, R., Wollnik, H., Münzel, J., Siegert, G., Jung, G., Koglin, E., 1978. Precision beta endpoint energy measurements of rubidium and caesium fission products with an intrinsic Ge-detector. Z. Phys. A 288, 105–106.

Yoshida, T., Nakasima, R., 1981. Decay heat calculations based on theoretical estimation of average beta- and gamma-energies released from short-lived fission products. J. Nucl. Sci. Technol. 18, 393–407.

Yoshida, T., Tachibana, T., 2000. Theoretical treatment of the asymptotic behavior of fission product decay heat toward very short cooling time. J. Nucl. Sci. Technol. 37, 491–497.

Yoshida, T., Tachibana, T., Storrer, F., Oyamatsu, K., Katakura, J., 1999. Possible origin of the gamma-ray discrepancy in the summation calculations of fission product decay heat. J. Nucl. Sci. Technol. 36, 135–142.

Yu Runlan, Guo Jingru, Cui Anzhi, Tang Peijia, Li Daming, Liu Daming, 1995. Measurement of the half-life of ^{79}Se using a radiochemical method. J. Radioanal. Nucl. Chem. 196, 165–170.

Zhang Shengdong, Guo Jingru, Cui Anzhi, Li Daming, Liu Daming, 1996. Measurement of the half-life of ^{126}Sn using a radiochemical method. J. Radioanal. Nucl. Chem. Lett. 212, 93–99.