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Table de RADIONUCLÉIDES

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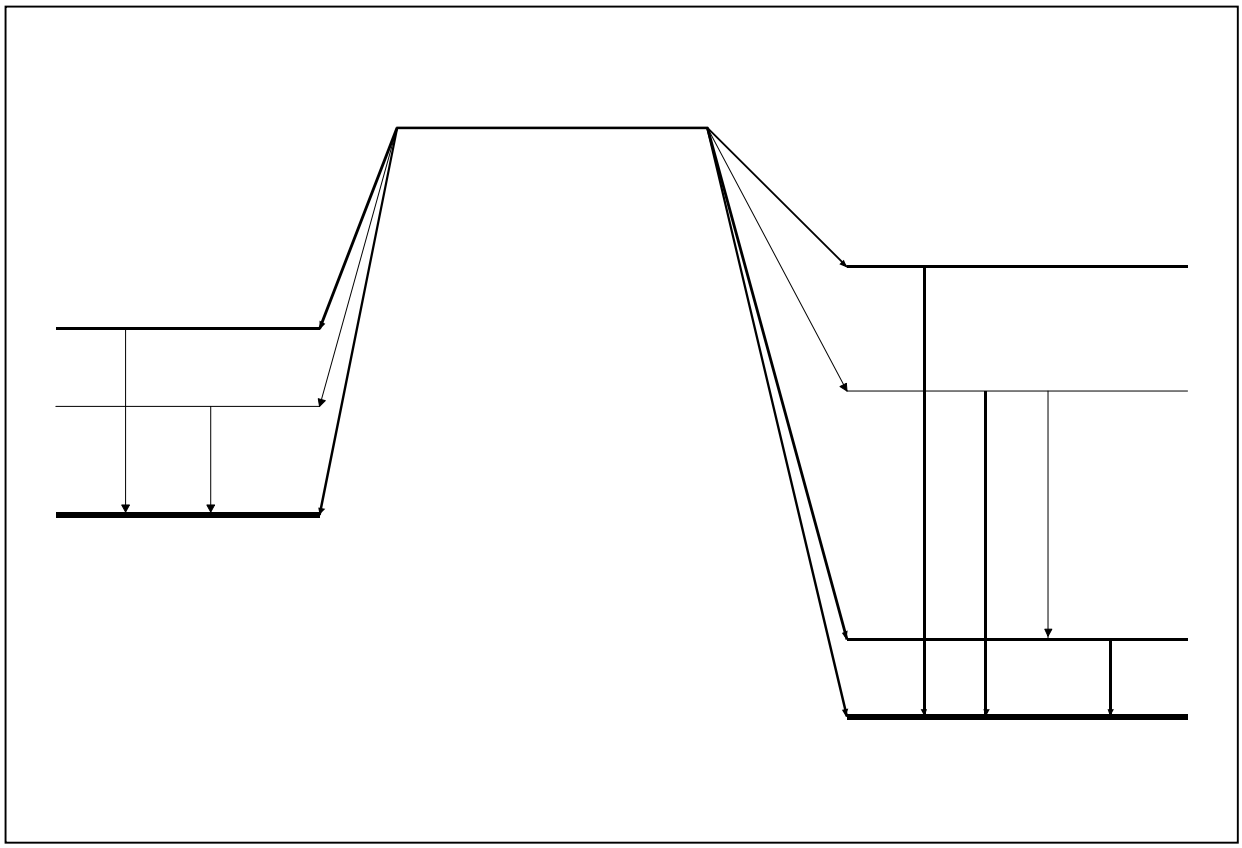
Tabelle der RADIONUKLIDE



INTRODUCTION

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"TABLE DE RADIONUCLÉIDES – Introduction"

Sommaire

Ce fascicule est une introduction à la Table de Radionucléides publiée sur papier et également à sa version informatisée NUCLÉIDE disponible sur CD-Rom. Il inclut une brève description des processus physiques de la radioactivité, l'énumération des règles d'évaluation conduisant aux valeurs recommandées, ainsi qu'un récapitulatif des symboles et des termes utilisés dans les différentes publications.

"TABLE OF RADIONUCLIDES - Introduction"

Summary

This volume is an introduction to the Table of Radionuclides published on paper and also to its computerised form NUCLÉIDE available on CD-Rom. It includes a brief description of the radioactivity physical processes, the enumeration of the evaluation rules leading to the recommended values, and a summary of the symbols and terms used in all the publications.

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TABLE DE RADIONUCLÉIDES
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INTRODUCTION

Édition 1999 : Marie-Martine BÉ, Bernard DUCHEMIN (BNM-CEA/LPRI)
Klauss DEBERTIN, Eckart SCHÖNFELD, Physikalisch-Technische Bundesanstalt (PTB)

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Chapter 1

PREFACE

The aim of this Table is to provide carefully evaluated data for radionuclides frequently used in science and technology. The evaluation is based on presently available experimental data and, in part, on theoretical consideration and the finally evaluated (and recommended) data are presented in a clear and easily readable form. This publication is a continuation of the earlier "Table de Radionucléides" (LMRI, France, 1974-1980), re-edited revised by F. Lagoutine, N. Coursol and J. Legrand (LMRI, France, l982-1986).

In order to update the data of the nuclides already present and to add new evaluations, the Laboratoire National Henri Becquerel (LNHB, France) and the Physikalisch-Technische Bundesanstalt (PTB, Germany) established a cooperative agreement; they were then joined by the Idaho National Engineering & Environmental Laboratory (INEEL, USA), the Lawrence Berkeley National Laboratory (LBNL, USA) and the Khlopin Radium Institute (KRI, Russia). This international collaboration is based on an informal agreement, the initial work of this group was to discuss and to agree on a methodology to be used in these evaluations. This is described in the chapter "Rules for Evaluation and Compilation".

In this new version, there are small changes in the presentation following international recommendations (e.g., use of the standard deviation instead of the uncertainty at the 99,7 % confidence level which was used before 1986) but the main objectives and contents are the same.

There is a separate section for each evaluated radionuclide, which can be practical for users and facilitates updating if new experimental work makes this necessary.

Moreover, LNHB developed a software NUCLÉIDE [76, 87] with the objectives of making it easier to update and add data and, obviously, to offer easy access to the nuclear and atomic decay data to the user by "click on the button" facilities.

Over the past years, several volumes of data and comments on how the recommended data have been obtained, were published as CEA Reports [82] or as BIPM Monograph [88].

New available evaluation of radionuclides are updated on :

http://www.bnm.fr/bnm-lnhb/NucData.htm

Each section includes :

- a decay scheme with the minimum information required for understanding the involved processes and levels;
- tables listing the nuclear data and atomic data directly relevant to the main emitted radiations;
- tables of probabilities for emission of alpha particles, various electron and photon ra-

diations which, in addition to the half-life, are the most useful data from the practical standpoint;

– the most important production method(s) and potential radioactive impurities. When one of these production modes involves activation by thermal neutrons, the cross section is given;

– the references employed with indications of parameters used from each. All references known by the author concerning a radionuclide have been examined, but only those employed in the evaluation are listed;

– finally, the evaluation date and the author of the evaluation, who can provide any additional information, are given in each section.

Chapter 2

SYMBOLS AND NOTATIONS

2.1 Units

s	second
min	minute
h	hour
d	day
a	year (1 a = 365,242 198 78 d or 31 556 926 s)
m	meter
J	joule
eV	electronvolt (1 eV = 1,602 177 $\times 10^{-19}$ J)
Bq	becquerel (1 Bq = 1 disintegration.s^{-1})
Δ	dose constant (J.Bq^{-1}.s^{-1})

2.2 Particles and quanta

e	electron
p	proton
n	neutron
d	deuteron
α	alpha particle
β^+	positron from β^+ decay
β^-	electron from β^- decay
γ	gamma quantum, photon emitted when a nucleus turns into a lower energy state
ν	neutrino ($\bar{\nu}$ antineutrino)
ce	internal conversion electron
ce_K	internal conversion electron, ejected from the K shell
ce_L	internal conversion electron, ejected from the L shell
e_A	Auger electron
e_{AK}	K-Auger electron
e_{AL}	L-Auger electron
KLL	KLL-Auger electron

KLX	KLX-Auger electron (X=M,N)
KXY	KXY-Auger electron (X=M,N; Y=M,N)
X	x-ray quantum, photon emitted during the rearrangement of the atomic shells
X_K	K X-ray quantum
X_L	L X-ray quantum
$e^{\pm}$	internal electron-positron pair
$\gamma^{\pm}$	gamma photon due to positron annihilation

2.3 Energies

E	energy, generally
E_α	alpha particle energy
E_{β^+max}	β^+ particle maximum energy
E_{β^-max}	β^- particle maximum energy
$\bar{E}_{\beta^+}$	β^+ particle mean energy
$\bar{E}_{\beta^+}$	β^- particle mean energy
E_γ	gamma quanta energy
E_{ph}	energy of photons which are not gamma quanta with regard to their origin
E_r	recoil energy
E_i	energy of a nucleus excited level
E_K	binding energy of an electron in the K shell
E_L	binding energy of an electron in the L shell
E_n	neutron energy
E_ν	neutrino energy
E_e	monoenergetic electron energy
E_{A_K}	K-Auger electron energy
E_{A_L}	L-Auger electron energy
E_{X_K}	K X-ray quanta energy
E_{X_L}	L X-ray quanta energy
E_{ce_K}	K conversion electron energy
E_{ce_L}	L conversion electron energy
Q_α	total available energy of alpha disintegration
Q_{β^+}	total available energy of β^+ disintegration
Q_{β^-}	total available energy of β^- disintegration
Q_ϵ	total available energy of electron capture transformation
q_K	energies of neutrinos after electron capture in the K shell
q_L	energies of neutrinos after electron capture in the L shell
q_M	energies of neutrinos after electron capture in the M shell
W	total energy of a β particle including its rest energy

2.4 Transition probabilities, emission probabilities and conversion coefficients

P_α	transition probability for an alpha transition
P_β	transition probability for a beta transition
P_ϵ	transition probability for an electron capture transition
P_γ	gamma ray emission probability
P_e	monoenergetic electron emission probability
P_X	X ray emission probability
P_{X_K}	K X-ray emission probability
P_{X_L}	L X-ray emission probability
P_{X_M}	M X-ray emission probability
P_{ce}	conversion electron emission probability
P_{ce_K}	K conversion electron emission probability
P_{ce_L}	L conversion electron emission probability
P_{ce_M}	M conversion electron emission probability
P_g	transition probability for a gamma transition including conversion electrons $P_g = P_\gamma + P_{ce}$
P_A	Auger electron emission probability
P_{A_K}	K-Auger electron emission probability
P_{A_L}	L-Auger electron emission probability
P_{A_M}	M-Auger electron emission probability
$P_{A_{KLL}}$	KLL-Auger electron emission probability
P_K	K-shell capture probability for an Electron Capture transition
P_L	L-shell capture probability for an EC transition
P_M	M-shell capture probability for an EC transition $(P_K + P_L + P_M + \ldots = 1)$
λ_n	probability for a given β transition
λ_0	probability for an allowed β transition
α_K	K-shell internal conversion coefficient
α_L	L-shell internal conversion coefficient
α_M	M-shell internal conversion coefficient
α_t	total internal conversion coefficient $(\alpha_K + \alpha_L + \alpha_M + \ldots = \alpha_t)$
α_π	internal pair creation coefficient

2.5 Other physical quantities and abbreviations

a_K	K-Auger yield, $a_K = 1 - \omega_K$
$\bar{a}_L$	mean L-Auger yield, $\bar{a}_L = 1 - \bar{\omega}_L$
A	(1) activity
	(2) mass number in ${}^{A}_{Z}\mathrm{X}_{N}$, where X is an element
B_K,B_{L_1}	exchange factor in the K shell, L1 subshell,...
C_n	shape factor of a β transition
C_0	shape factor of an allowed β transition
E0, E1, E2, EL	electric monopole, dipole, quadrupole, 2L-pole
f	(1) component of radial functions of the electron
	(2) alpha particle collision frequency
f_0	Fermi integral for an allowed transition
f_1,f_2,...	Fermi integrals for unique first forbidden, second forbidden,... transitions
ft	comparative half-life
f_{12},f_{13},f_{23}	probabilities of Coster-Kronig transitions
F	hindrance factor
$F(t)$	correction factor for radioactive decay
g	(1) coupling constant of weak interactions
	(2) components of radial functions of the electron
J	quantum number of total angular momentum
J	Joule
K, L, M ...	electron shells
K/L	ratio $P_{ce_K}/P_{ce_L} = \alpha_K/\alpha_L$
K/LM	ratio $P_{ce_K}/(P_{ce_L} + P_{ce_M}) = \alpha_K/(\alpha_L + \alpha_M)$
K/LMN	ratio $P_{ce_K}/(P_{ce_L} + P_{ce_M} + P_{ce_N}) = \alpha_K/(\alpha_L + \alpha_M + \alpha_N)$
KLX/KXY	ratio $P_{A_{KLX}}/P_{A_{KXY}}$
L	orbital angular momentum quantum number
L_1, L_2, L_3	L electron subshells
m_0	electron rest mass
max	maximum
min	minimum
av	average
M	atomic mass
M_N	mass of the nucleus
M1, M2, ML	magnetic dipole, quadrupole, 2L-pole
n_K,n_L	mean number of vacancies in the K shell and L shell created during the disintegration of one nucleus of a given radionuclide
n_{KL}	total number of L vacancies created by K $\rightarrow$ L transfer, i.e. mean number of vacancies in the L shell produced by one vacancy in the K shell

N	(1) number of neutrons in ${}^{A}_{Z}\mathrm{X}_{N}$ where X is an element
	(2) number of radioactive atoms
P	penetrability for the potential barrier
R	radius of the nucleus
r_0	radius of the nucleus in units of $\hbar/m_0c$
S	intrinsic spin
t	time
$T_{1/2}$	radioactive half-life
v_0	velocity of the α particle
V_{L_i}	Coster-Kronig vacancies
Z	atomic number in ${}^{A}_{Z}\mathrm{X}_{N}$ where X is an element
δ	ratio $\delta^2 = E(L+1)/M(L)$
	mixing of different multipolarities
ϵ	transition by electron capture (EC)
λ	decay constant
π	parity
σ	total neutron capture cross section
σ^0	2200 m.s^{-1} neutron capture cross section
ω_K	K-shell fluorescence yield
ω_{L1},ω_{L2},ω_{L3}	fluorescence yield in the L_1,L_2,L_3 subshells
$\bar{\omega}_L$	mean L-shell fluorescence yield
$\bar{\omega}_M$	mean M-shell fluorescence yield

Chapter 3

DESCRIPTION OF RADIOACTIVE PROCESSES

3.1 Brief reminder of some definitions

Nuclide: A nuclide is a species of atoms characterized by an atomic number Z (proton number) and a mass number M (nucleon number).

Radionuclide: A radionuclide is a radioactive nuclide.

Transition: A transition is a process in which an atomic nucleus undergoes a transformation by disintegration or de-excitation.

Disintegration: A disintegration of an atomic nucleus is the spontaneous transformation of the nucleus into another one giving rise to a change in the atomic number, or into two or more nuclei (fission), or, in the case of an isomer, a transition to a lower energy state of the same nucleus. Disintegration leaves the daughter nucleus in the ground state or in an excited state, the de-excitation occurring usually through one or more γ transitions. While in α decay there is also a change in the mass number, in β^-decay, β^+ decay and electron capture the mass number remains unchanged.

Isomer: An isomer is a nuclide in an excited state having a non-negligible half-life, liable to de-excitation by a γ transition (isomeric transition, e.g. $^{103}\mathrm{Rh}^{\mathrm{m}}$), or to any other transition, such as β decay or electron capture (e.g. $^{110}\mathrm{Ag}^{\mathrm{m}}$, $^{115}\mathrm{In}^{\mathrm{m}}$).

Transition probability: The transition probability assigned to a specific transition is the probability that this transition occurs when one nucleus of this radionuclide disintegrates.

The transition probability includes all processes which lead from the initial level to the final level, where the latter may belong to the daughter nucleus or to the same nucleus.

With respect to different transition types, the transition probability is the probability of the transformation of a nuclide in a given energy state *via* the emission of particles (α, β^- , β^+) or the capture of electrons from the atomic shell (denoted by ϵ or EC) into a specific state of their daughter nuclei (excited state or ground state) or *via* the emission of gamma quanta and conversion electrons into a lower energy state of nuclei of the same nuclide.

According to its above definition the probability of a transition has a value between 0 and 1. A radionuclide may decay by one type of transitions only or it may have branches

of different types (for example EC and β^+). In each case the sum of the transition probabilities of all branches to the daughter nuclide(s) is exactly 1.

In the past, intensity, branching, abundance and other notations have been used instead of transition probability. To have uniformity and to distinguish clearly between transition probability and emission probability the above notations are avoided here. Note: in quantum mechanics the term transition probability per unit time is used. It should not be confused with the dimensionless transition probability used here.

Emission probability: The emission probability assigned to the particles or quanta (specified by type and energy) emitted by a radionuclide is the probability that such a particle or quantum will be emitted when one nucleus of this radionuclide disintegrates, *i.e.* the emission probability is the mean number of particles or quanta emitted per disintegration of one nucleus.

According to the above definition the emission probability for α-, β- and γ- radiation has a value between 0 and 1. For X-rays, Auger electrons and γ due to positron annihilation, the emission probability may exceed 1 due to the following reasons:

- vacancies in the K-shell and other shells can be produced by EC transitions as well as by inner conversion of γ -transitions;
- the number of vacancies in the L(M) shell, created by one vacancy in the K(L) shell can be larger than 1;
- two photons are emitted per one emitted positron.

For these reasons, in the tables, the notation "number of electrons (or photons or alpha) per disintegration" are used throughout.

There are the following relationships between transition probabilities and emission probabilities :

- the transition probability for an α transition is equal to the mean number of α particles emitted per disintegration;
- the transition probability for a β transition is equal to the mean number of β particles emitted per disintegration;
- the transition probability for an EC transition is composed by the contributions of capture processes from the K, L, M, ... shells. It is related to the emission probabilities for X rays and Auger electrons *via* fluorescence yields and other atomic shell data;
- the transition probability of a γ transition is the sum of the emission probabilities of the mean number of photons and conversion electrons from different shells (K, L, M, ...) emitted per disintegration.

Energy of disintegration : The energy of disintegration is the available energy from the ground state of the parent to the ground state of the daughter. It corresponds to the difference in atomic masses between these levels.

Activity : The activity, A, of an amount of radioactive nuclide in a particular energy state at a given time is the quotient of dN by dt, where dN is the expected value of the number of spontaneous nuclear transitions from that energy state in the time interval dt :

$$A = \frac{dN}{dt} \tag{3.1}$$

(Definition according to the International Commission on Radiation Units and Measurements (ICRU)[1]. The "particular energy state" is the ground state of the nuclide

unless otherwise specified, e.g. in the case of isomers.

The special name for the unit of activity is **becquerel (Bq)**, 1 Bq = one disintegration per second.

The old unit of activity, the *curie* (Ci), is still used in some medical circles; its value is $3{,}7 \times 10^{10}$ Bq.

Radioactive decay : The radioactive decay is the decrease of the activity of a radioactive substance with time by spontaneous nuclear transformations. It is expressed by the equations :

$$\frac{dN}{dt} = -\lambda N \tag{3.2}$$

$$N = N_0 e^{-\lambda t} \tag{3.3}$$

$$A = A_0 e^{-\lambda t} \tag{3.4}$$

where N is the number of atoms of the corresponding radionuclide consisting of nuclei being in the same energy state at time t, N_0 is the number of such atoms at time $t = 0$ and λ is the decay constant. Analogously, A and A_0 are the activity of the radioactive source or substance at time t and at time $t = 0$. When several nuclear transformation modes are in competition with partial decay constants λ_i (e.g. $^{110}\mathrm{Ag^m}$, $^{58}\mathrm{Co}$, $^{186}\mathrm{Re}$, etc...), the decay constant λ is written :

$$\lambda = \sum \lambda_i \tag{3.5}$$

The half-life $T_{1/2}$ is the time required for the initial number of atomic nuclei, in a given state, to decrease by a factor of two.

$$T_{1/2} = \frac{\ln 2}{\lambda} \tag{3.6}$$

The mean life or expected life-time $t = 1/\lambda$ is frequently employed.

Remark : in practice, we advise against using the expression "partial half-life" defined by $(T_{1/2})_i = \ln 2/\lambda_i$, which has no practical meaning. One such example is $^{252}\mathrm{Cf}$, with a half-life of 2,6 years, which can disintegrate by α emission or by spontaneous fission, and which therefore has two partial decay constants λ_α and λ_F. The activity of a source of $^{252}\mathrm{Cf}$ is given by equations (3.2) and (3.4). The α emission rate is $\lambda_\alpha N$ and that of spontaneous fission is $\lambda_F N$, each of these rates decreasing with $\mathrm{e}^{-\lambda \mathrm{t}}$ and not with $\mathrm{e}^{-\lambda_\alpha \mathrm{t}}$ or $\mathrm{e}^{-\lambda_\mathrm{F} \mathrm{t}}$.

The decay constants and half-lives are, in principle, independent of extranuclear conditions. In fact, radioactivity is not a purely nuclear phenomenon [2]. Changes occurring in the environment, more precisely in the electrons of the external shells, can cause decay constant variations [3]. The different types of nuclear transformation able to give rise to observable changes are those in which the orbital electrons contribute directly to the nuclear transformation. In the case of $^{7}\mathrm{Be}$, which disintegrates by electron capture, differences, $\Delta\lambda/\lambda$, greater than 10^{-3} have been observed between various chemical compounds. In the case of $^{99}\mathrm{Tc^m}$, partly de-excited by a strongly converted γ transition of 2,17 keV, differences of the order of $0{,}3 \times 10^{-3}$ have also been observed.

3.2 Disintegration modes

Only α,β^-,β^+ and ϵ (electron capture) decays are examined here. The other existing modes of disintegration, such as spontaneous fission, proton emission and delayed neutron emission, will be examined later, if necessary, in an appendix.

Nuclei of a given radionuclide can disintegrate *via* a single transition mode, for example by β^- disintegration only or *via* several transition modes which are in competition with each other, such as β^+ and electron capture or β^- and α.

Isomers can de-excite or undergo radioactive disintegration (e.g. $^{110}\mathrm{Ag^m}$, $^{115}\mathrm{In^m}$).

3.2.1 α decay

A nucleus with atomic number Z and mass number A disintegrates by emitting an α particle, and giving a nucleus with atomic number $Z-2$ and mass number $A-4$;

$$ {}^{A}_{Z}\mathrm{X}_N \rightarrow {}^{A-4}_{Z-2}\mathrm{Y}_{N-2} + {}^{4}_{2}\mathrm{He}_2 $$

The created nucleus may be in an excited energy state E_i.

Hence the α disintegration energy is :

$$ Q_\alpha = E_{\alpha_i} + E_i + E_{r_i} \tag{3.7} $$

where E_{α_i} is the energy of the emitted α particle, constant for a given transition, and E_{r_i} the recoil energy :

$$ E_{r_i} = \frac{M_\alpha}{M_N + M_\alpha}\Big[Q_\alpha - E_i\Big] \tag{3.8} $$

with M_N : mass of the recoiling daughter nucleus and M_α : mass of the α-particle.

Using (3.7) and (3.8) :

$$ E_{r_i} = \frac{M_\alpha}{M_N} E_{\alpha_i} \tag{3.9} $$

Probability of α decay

This is determined by means of the theory of the one-body model. When an α particle moves within a spherical nucleus and is held there by the Coulomb potential barrier, a certain probability exists that the α particle will escape from the nucleus, although the potential energy represented by the height of the barrier is greater than its kinetic energy (tunneling).

The decay constant for a given α transition is expressed by :

$$ \lambda = f\,P = \frac{V_0}{R}\,P \tag{3.10} $$

where :

f	:	collision frequency of the α particle within the potential well,
V_0	:	velocity of the α particle within this potential well,
R	:	radius of the nucleus,
P	:	penetrability of the potential barrier.

P is a function of the atomic number, the mass number, the radius of the nucleus, and the characteristics of the potential barrier.

The α transitions of even-even nuclei from ground state to ground state have the highest decay constants. They are adequately described by theoretical expressions based on (3.10), or by the following equation which is derived from (3.10), for a given atomic number :

$$\lg (T_{1/2})_i = AQ^{-1/2} + B \tag{3.11}$$

where $(T_{1/2})_i$: partial half-life of the transition, Q : total energy available for this transition, A and B : constants calculated on the basis of experimental values of Q and transition probabilities from ground state to ground state.

The theory of the one-body model completely ignores the probability of preformation of the α particle, as well as the effect of the angular momentum carried off by the α particle on the penetrability of the potential barrier. This means that the experimental values of partial half-lives other than those of even-even nucleus transitions from ground state to ground state, are generally greater than calculated values. They are hindered at various degrees [4,5].

Hindrance factor

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

$$F = \frac{(T_{1/2})_{i\,exp}}{(T_{1/2})_{i\,th}} \tag{3.12}$$

where:

$(T_{1/2})_{i\,exp}$: experimental partial half-life calculated from the value of the transition probability of the quoted α transition ;

$(T_{1/2})_{i\,th}$: theoretical partial half-life.

All even-even nucleus transitions from ground state to ground state have, by definition, $F = 1$.

Partial half-lives $(T_{1/2})_{i\,th}$ can be calculated by means of a selected theory of α decay [6], or derived from equation (3.11). In this case, the A and B constants for even-odd or odd-odd nuclei are derived by interpolation of the adjacent values of even-even nuclei.

For the even-even nucleus α transitions to excited levels, the hindrance factor which is caused, for the initial levels, by the angular momentum carried off by the α particle, slowly and steadily increases with the energy of the excited level (e.g. ^{226}Ra, $F \simeq 5$ for the second excited level).

Some transitions of even-odd and odd-odd nuclei, which generally do not go towards the ground state, exhibit a low hindrance factor. They are called "favored" (e.g. ^{241}Am) and frequently correspond to a transition between initial and final states with identical spins and parities.

3.2.2 β decay

During a β decay, the mass number A remains unchanged and the atomic number Z varies by one unit.

β^- decay : an electron and an anti-neutrino are emitted, resulting from the transformation of a nucleus neutron to a proton.

$$\begin{cases} {}^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z+1}\mathrm{Y} + \beta^- + \bar{\nu} \\ \mathrm{n} \longrightarrow \mathrm{p} + \beta^- + \bar{\nu} \end{cases}$$

The energy of a β^- transition, corresponding to the maximum β-energy emitted, and ignoring the recoil energy, is :

$$E_{\beta^- max} = Q^- - E_i$$

where Q^- : energy of disintegration, equal to the difference in atomic masses between the ground states of the parent and daughter, and E_i : energy of the level to which the decay occurs.

β^+ **decay**, the process is described similarly :

$$\begin{cases} {}^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z-1}\mathrm{Y} + \beta^+ + \nu \\ \mathrm{p} \longrightarrow \mathrm{n} + \beta^+ + \nu \end{cases}$$

$$E_{\beta^+ max} = Q^+ - 2m_0c^2 - E_i \tag{3.13}$$

where Q^+ : energy of disintegration, with

$$2\,m_0c^2 = 1{,}021\,998 \text{ MeV}$$

m_0 being the electron mass at rest.

A β^+ disintegration can occur, if :

$$Q^+ - E_i > 2\,m_0c^2 \tag{3.14}$$

Mean energy : the energy of a β transition is shared between the electron and the neutrino with a continuous distribution for the two particles extending from 0 up to $E_{\beta max}$.

If $N(E)\,dE$ is the number of β particles with energy between E and $E + dE$, the mean energy is written :

$$\bar{E} = \int_0^{E_{\beta max}} E\ N(E)\ dE \Big/ \int_0^{E_{\beta max}} N(E)\ dE \tag{3.15}$$

Probability of β decay

The β decay is governed by the laws of weak interaction between the electron-neutrino pair and the nucleus and incorporates a very low coupling constant $g = 1{,}41 \times 10^{-56}$ J.cm^3 .

The probability per unit time for an atomic nucleus to decay by a given β transition is [7,8], in natural units ($\hbar = m_0 = c = 1$) :

$$\lambda_n = \int_1^{W_0} N(W)\ dW \tag{3.16}$$

$$\lambda_n = \frac{g^2}{2\pi^3} \int_1^{W_0} W(W^2-1)^{1/2}\,(W_0 - W)^2\,F(Z,W)\,L_0(Z,W)\,(1 + \delta_R(Z,W))\,C_n\,dW \tag{3.17}$$

where :

n	:	order of forbiddenness of the transition
$N(W)\,dW$	:	number of β particles emitted per unit time with energy between W and $W + dW$
$F(Z,W)$	:	Fermi function
$L_0(Z,W)$	:	screening correction
$\delta_R(Z,W)$	:	electromagnetic correction
C_n	:	shape factor
Z	:	atomic number of the daughter
W	:	total energy of the β particle
W_0	:	maximum total energy of the β particle $W_0 = Q + 1$ for a β^- transition $W_0 = Q - 1$ for a β^+ transition Q is the transition energy

The term $W(W^2 - 1)^{1/2}\ (W_0 - W)^2$ is the statistical factor determining the distribution of energy between the electron and the neutrino.

The Fermi function $F(Z,W)$ and the term $L_0(Z,W)$ take into account the perturbation of the electron wave function by the electric field of the nucleus. This Coulomb interaction causes at low spectral energies an enrichment of electrons and a depletion of positrons (Figure 3.1).

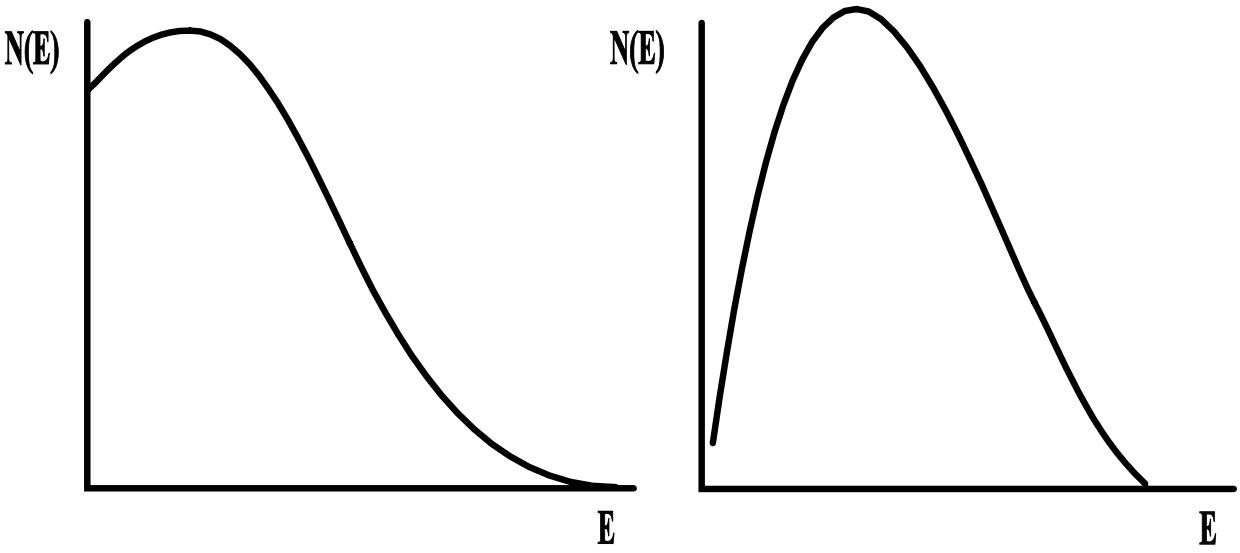


Figure 3.1 – *Examples of the typical β^- (left) and β^+ (right) spectra of an allowed transition.*

The term $(1 + \delta_R(Z,W))$ takes into account the electromagnetic corrections ; for example the emission of photons due to internal bremsstrahlung during the decay.

The shape factor may be deduced from the transition characteristics (nuclear matrix elements, etc.).

Types of transitions and selection criteria

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 an orbital angular momentum with quantum number L_β, as well as an intrinsic spin S_β which can be: 1, -1 or 0. The conservation of the total angular momentum requires that:

$$J_i = J_f + L_\beta + S_\beta \tag{3.18}$$

$$\Delta J = J_i - J_f \tag{3.19}$$

as well as the parity relationship:

$$\pi_f \, \pi_i = (-1)^{L_\beta} \tag{3.20}$$

The transitions in which $L_\beta = 0$ are called allowed, those in which $L_\beta = n$ are called forbidden to the n^{th} order.

From this, the selection criteria can be derived:

Classification of β-transition types

Type	Order of forbiddenness	ΔJ	$\pi_f \, \pi_i$
Super-allowed		0	+1
Allowed		0,+1	+1
Forbidden unique	1	± 2	–1
	2	± 3	+1
	3	± 4	–1
	4	± 5	+1
	(ΔJ– 1) nth	> 1	$(-1)^{(\Delta J-1)}$
Forbidden	1	0, ± 1	–1
	2	± 2	+1
	3	± 3	–1
	4	± 4	+1
	(ΔJ) nth	> 1	$(-1)^{\Delta J}$

For an allowed transition, the shape factor C_0 is independent of energy, and in this case the probability λ_0 of the transition is:

$$\lambda_0 = \frac{g^2}{2\,\pi^3} \, f_0(Z,W_0) \, C_0 \tag{3.21}$$

where:

$$f_0(Z,W_0) = \int_1^{W_0} W(W^2-1)^{1/2} \, (W_0 - W)^2 \, F(Z,W) \, dW \tag{3.22}$$

is the Fermi integral.

For unique forbidden transitions, the shape factor may be evaluated as a function of the energy. For non-unique forbidden transitions, it cannot be evaluated, because some matrix elements are unknown.

Comparative half-life, lg ft

In order to obtain information on the shape factor, and on level spins and parities, and to make a rough classification of β transitions as a function of the forbiddenness degree, it is of great interest to calculate the comparative half-lives, ft, with :

$$t_i = \frac{T_{1/2}}{P_{\beta_i}} = \frac{\ln\ 2}{\lambda_i} \tag{3.23}$$

where :

$T_{1/2}$	:	half-life in seconds,
P_{β_i}	:	probability of the transition,
λ_i and t_i	:	probability and "partial half-life" of the transition respectively.

For an allowed transition :
using (3.21) and (3.23)

$$f_0 t = \frac{2\pi^3\ \ln\ 2}{g^2\ C_0} \tag{3.24}$$

For forbidden transitions : [7]

$$f_n t = \frac{2\pi^3\ \ln\ 2}{g^2\,\eta^2} \tag{3.25}$$

with :

$$f_n = \int_1^{W_0} W(W^2-1)^{1/2}\ (W_0 - W)^2\ F(Z,W)\ \frac{C_n}{\eta^2}\ dW \tag{3.26}$$

where η^2 is a combination of nuclear matrix elements.

The function f_n can only be calculated for unique transitions. However, for non-unique forbidden transitions, it is accepted that $C_n \simeq C_0$ to determine experimental values of ft.

In view of the extremely wide variety of the ft values, it is preferable to calculate and tabulate $\lg ft$ rather than ft [9], as $\lg\ ft$ varies by about 3 for so-called super-allowed transitions, and increases with the order of forbiddenness up to a value above 20 for fourth-forbidden transitions.

β transitions are distributed as a function of $\lg ft$ as follows [10] :

Type of transition	$\lg\ ft$
Super-allowed	3,48–3,5
Allowed	3,5–12,5
First-forbidden	5,1–17
Second-forbidden	11–15,5
Unique first-forbidden	8,5–11,7 ($\lg\ f_1 t$)
Unique second-forbidden	12,8–19
Forbiddenness greater than second	$> 17{,}6$

3.2.3 Electron capture decay

In this process, an orbital electron is captured by the nucleus :

$$\begin{cases} {}^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z-1}\mathrm{Y} + \nu \\ \mathrm{p} + \mathrm{e}^{-} \longrightarrow \mathrm{n} + \nu \end{cases}$$

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

$$q_x = Q^+ - E_i - E_x \tag{3.27}$$

where :

Q^+	:	energy of disintegration corresponding to the difference in atomic masses between parent and daughter ground state,
E_i	:	energy of the nuclear level towards which the electron capture occurs,
E_x	:	binding energy of the electron in the X shell (or the subshell) in the final atom,
$Q^+ - E_i$	:	transition energy.

The energy condition determining whether capture can occur in the X shell is :

$$Q^+ - E_i \geq E_x \tag{3.28}$$

furthermore, if :

$$Q^+ - E_i \gg E_x \tag{3.29}$$

the electron capture is far more probable in the K shell than in the other shells. Moreover, if :

$$Q^+ - E_i \geq 2\, m_0 c^2 \tag{3.30}$$

the β^+ emission is in competition with the electron capture. For an electron capture transition, designated by ϵ, with a probability P_ϵ , the relative capture probabilities are :

$$P_K + P_L + P_M + P_N + \ldots = 1 \tag{3.31}$$

Recoil energy : this is obtained from the laws of momentum and energy conservation :

$$E_r = \frac{q_x^2}{2\, M_N\, c^2} \tag{3.32}$$

where M_N : mass of the nucleus.

This is generally ignored, except for ^{7}Be, where $E_r = 57$ eV.

Probability for a transition by electron capture

Electron capture is a weak interaction process to which the β-disintegration theory can be applied directly.

Allowed transitions : according to theory, the probability for capture per unit time in the K shell is given by the expression [11,12] :

$$\lambda_k = \frac{g^2\, |M_{0,1}|^2}{4\pi^2}\; q_K^2\; g_K^2\; B_K \tag{3.33}$$

The capture probabilities in the subshells L_1 and L_2 are given by identical expressions, in which q_K^2 is replaced by $q_{L_1}^2$ or $q_{L_2}^2$, g_K^2 by $g_{L_1}^2$ or $f_{L_2}^2$ and B_K by B_{L_1} or B_{L_2}. Capture in the L_3 subshell is negligible for allowed transitions.

$|M_{0,1}|^2$: nuclear matrix element,
q_K, q_{L_1}, q_{L_2} : neutrino energies,
f,g : components of the electron radial wave functions,
B_K, B_{L_1}, B_{L_2} : exchange factors.

Except for the B_K factor, expression (3.33) is identical to that given for the β disintegration probability, the statistical factor being reduced to $\frac{\pi}{2}\, q_K^2\, g_K^2$.

The exchange factor B, which takes into account atomic influences on the capture probability, incorporates two effects : the incomplete recovery of initial and final atomic states due to the charge change in the nucleus, and the exchange effect itself, as the capture in a shell can be achieved by several processes which are not experimentally distinguishable. For instance, a L_1 vacancy can be obtained mainly by direct capture of an L_1 electron, but also by K capture with simultaneous exchange of L_1 and K electrons, or by capture of an M_1 electron with simultaneous exchange of M_1 and L_1 electrons.

These two effects, recovery and exchange, have opposite signs and partially counteract each other. The recovery effect predominates for low atomic numbers, and the exchange effect for high atomic numbers.

The capture probabilities P_K, P_L, $P_{L_1}, \ldots$ are normally calculated by means of the ratios :

$$\frac{P_L}{P_K} = \frac{P_{L_1}}{P_K}\left[1 + \frac{P_{L_2}}{P_{L_1}}\right] \tag{3.34}$$

$$\frac{P_{L_1}}{P_K} = \frac{g_{L_1}^2\, q_{L_1}^2}{g_K^2\, q_K^2}\, X^{L_1/K} \quad \text{with} \quad X^{L_1/K} = \frac{B_{L_1}}{B_K} \tag{3.35}$$

$$\frac{P_{L_2}}{P_{L_1}} = \frac{f_{L_2}^2\, q_{L_2}^2}{g_{L_1}^2\, q_{L_1}^2}\, \frac{B_{L_2}}{B_{L_1}} \simeq \frac{f_{L_2}^2}{g_{L_1}^2}\, \frac{B_{L_2}}{B_{L_1}} \tag{3.36}$$

The ratios $\frac{g_{L_1}^2}{g_K^2}$ and $\frac{f_{L_2}^2}{g_{L_1}^2}$ have been calculated by several authors [13,14,15] together with exchange factors [15,16,17,18].

The capture probabilities in the M shell are determined similarly to those in the K and L shells by means of the ratios :

$$\frac{P_M}{P_L} = \frac{P_M}{P_{L_1}}\, \frac{P_{L_1}}{P_L} \tag{3.37}$$

where $\frac{P_{L_1}}{P_L}$ is deduced from (3.34) and (3.35), moreover :

$$\frac{P_M}{P_{L_1}} = \frac{P_{M_1}}{P_{L_1}}\left[1 + \frac{P_{M_2}}{P_{M_1}}\right] \tag{3.38}$$

$$\frac{P_M}{P_{L_1}} \simeq \frac{g_{M_1}^2\, q_{M_1}^2}{g_{L_1}^2\, q_{L_1}^2}\left[1 + \frac{f_{M_2}^2}{g_{M_1}^2}\right] X^{M_1/L_1} \tag{3.39}$$

with $X^{M_1/L_1} = \dfrac{B_{M_1}}{B_{L_1}}$.

Captures in the M_3, M_4, M_5 subshells are assumed to be negligible.

More general expressions including captures in the lower shells may be written [15]:

$$\frac{P_{MN}}{P_L} = \frac{P_{MN}}{P_{L_1}} \; \frac{P_{L_1}}{P_L} \tag{3.40}$$

$$\frac{P_{MN}}{P_{L_1}} = \frac{P_{M_1}}{P_{L_1}} \left[1 + \frac{P_{M_2} + P_{N_1} + P_{N_2} + \ldots}{P_{M_1}} \right] \tag{3.41}$$

Unique forbidden transitions : the capture probability in the K shell is written [11,15] :

$$\lambda_K = \frac{g^2 \; |M_{\Delta J}|^2}{4\pi^2} \; \frac{(q_K \; r_0)^{2(\Delta J - 1)}}{[\,(2\Delta J - 1) \; !!\,]^2} \; q_K^2 \; g_K^2 \; B_K \tag{3.42}$$

where r_0 : nucleus radius in units of $\hbar / m_0 c$.

$$n = \Delta J - 1 \qquad \Delta J = 2,3,\ldots \qquad \pi_f / \pi_i = (-1)^n \tag{3.43}$$

The capture probabilities in the L_1 and L_2 subshells are indentically obtained and the contribution due to the capture in the L_3 subshell must be added. They are determined by means of the following ratios :

$$\frac{P_L}{P_K} = \frac{P_{L_1}}{P_K} \left[1 + \frac{P_{L_2}}{P_{L_1}} + \frac{P_{L_3}}{P_{L_1}} \right] \tag{3.44}$$

$$\frac{P_{L_3}}{P_{L_1}} = \frac{3(\Delta J - 1)(2\Delta J - 1)}{(q_{L_1} \; r_0)^2} \; \frac{g_{L_3}^2 \; B_{L_3}}{g_{L_1}^2 \; B_{L_1}} \tag{3.45}$$

$$\frac{P_L}{P_K} \simeq \frac{g_{L_1}^2 \; q_{L_1}^{2\Delta J}}{g_K^2 \; q_K^{2\Delta J}} \; X^{L_1/K} \left[1 + \frac{f_{L_2}^2 \; B_{L_2}}{g_{L_1}^2 \; B_{L_1}} + \frac{3(\Delta J - 1)(2\Delta J - 1)}{(q_{L_1} \; r_0)^2} \; \frac{g_{L_3}^2 \; B_{L_3}}{g_{L_1}^2 \; B_{L_1}} \right] \tag{3.46}$$

$\lg ft$: the comparative half-lives for electron capture transitions are calculated similarly to those of β transitions [9].

3.2.4 ϵ/β^+ ratio

For nuclides decaying by electron capture and β^+ disintegration, when the electron capture is in competition with the β^+ emission, the ratio of probabilities $P\epsilon/P_{\beta^+}$, or more simply ϵ/β^+, is written :

$$\frac{\epsilon}{\beta^+} = \frac{\epsilon}{\beta^+} \; [P_K + P_L + P_M + \ldots] \tag{3.47}$$

$$\frac{\epsilon}{\beta^+} = \frac{\epsilon \; P_K}{\beta^+} \left[1 + \frac{P_L}{P_K} + \frac{P_M}{P_K} + \ldots \right] \tag{3.48}$$

The terms in square brackets may be calculated by equations (3.34) to (3.46).

Let $\epsilon P_K = \epsilon_K$; $\dfrac{\epsilon_K}{\beta^+}$ is given by :

$$\frac{\epsilon_K}{\beta^+} = \frac{\pi}{2} \frac{q_K^2 \; g_K^2 \; B_K}{f_0} \tag{3.49}$$

for an allowed transition;

$$\frac{\epsilon_K}{\beta^+} = \frac{\pi}{2} \frac{q_K^{2\Delta J} \; g_K^2 \; B_K}{f_{\Delta J-1}} \tag{3.50}$$

for an unique forbidden transition.

3.3 γ transitions

A γ transition occurs when a nucleus is de-excited towards a lower energy level that may or may not, be the ground state. This leads to the emission of a γ ray or a conversion electron and very rarely, when energy conditions make it possible, of an electron-positron pair.

The γ transition probability is :

$$P_g = P_\gamma + P_{ce} + P_{e^\pm} \tag{3.51}$$

where P_γ, P_{ce} and $P_{e^\pm}$ are the γ emission, conversion electron emission and electron-positron pair emission probabilities, respectively.

3.3.1 γ -ray emission

The energy of the emitted γ ray is :

$$E_\gamma = (E_i - E_f) - E_r \tag{3.52}$$

where $E_i - E_f$: energy difference between the initial and the final level of the γ transition, E_r : recoil energy of the nucleus in its final state, given by :

$$E_r = \frac{(E_\gamma)^2}{2M_N \, c^2} \tag{3.53}$$

M_N: mass of the recoiling daughter nucleus.

The recoil energy is negligible, except for high γ energies and low atomic numbers. For example, for the 1 369 keV γ emission of ^{24}Na, $E_r = 42$ eV.

3.3.2 Internal conversion

The de-excitation energy of the nucleus can also be transferred directly to an X-shell electron (X = K, L, M ...) which is ejected from the atom, carrying off the energy:

$$E_{ce\,X} = E_\gamma - E_X \tag{3.54}$$

where E_X : binding energy of the electron in the X shell.

Internal conversion coefficients :
for a given transition, the internal conversion coefficient of the electron in the K shell is defined by :

$$\alpha_K = \frac{P_{ce_K}}{P_\gamma} \tag{3.55}$$

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

The following quantities are similarly defined :

$$\alpha_L = \frac{P_{ce_L}}{P_\gamma}, \;\; \alpha_{L_i} = \frac{P_{ce_{L_i}}}{P_\gamma} \;\; (i = 1,\, 2,\, 3) \tag{3.56}$$

with $\alpha_L = \alpha_{L_1} + \alpha_{L_2} + \alpha_{L_3}$

$$\alpha_{M_i} = \frac{P_{ce_{M_i}}}{P_\gamma} \quad (i = 1,\, 2,\, 3,\, 4,\, 5) \tag{3.57}$$

The total conversion coefficient is:

$$\alpha_t = \alpha_K + \alpha_L + \alpha_M + \ldots = \frac{P_{ce}}{P_\gamma} \tag{3.58}$$

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

This leads to the following relations, neglecting $P_{e^\pm}$:

$$P_{ce} = \frac{\alpha_t}{1+\alpha_t}\, P_g, \;\; P_\gamma = \frac{P_g}{1+\alpha_t}, \;\; P_{ce_X} = \frac{\alpha_X}{1+\alpha_t}\, P_{g_X} \quad (\mathrm{X} = \mathrm{K,L,M}\ldots) \tag{3.59}$$

The K/L, K/LM, K/LM..., ratios are also employed and are defined as follows :

$$\frac{K}{L} = \frac{P_{ce_K}}{P_{ce_L}} = \frac{\alpha_K}{\alpha_L} \tag{3.60}$$

$$\frac{K}{LM} = \frac{P_{ce_K}}{P_{ce_L} + P_{ce_M}} = \frac{\alpha_K}{\alpha_L + \alpha_M} \tag{3.61}$$

$$\frac{K}{LM\ldots} = \frac{P_{ce_K}}{P_{ce_L} + P_{ce_M} + \ldots} = \frac{\alpha_K}{\alpha_L + \alpha_M + \ldots} \tag{3.62}$$

Internal conversion depends on the initial state of the electron (atomic shell or subshell), on the atomic number Z and on the nuclear transition. It increases with multipolarity and decreases with increasing γ energy, becoming negligible for high energies.

Internal conversion is influenced by the finite size of the nucleus in relation with two processes : a static owing to the finite distribution of nuclear charge, and a dynamic one (penetration process) which expresses the non-zero conversion probability within the nuclear volume. This penetration effect can become significant only in some specific cases such as : γ transition with high hindrance, heavy nuclei, etc...

3.3.3 Internal pair creation

This process is possible only if the transition energy is greater than $2\,m_0\,c^2 = 1{,}022$ MeV, with the electron-positron pair carrying off the energy :

$$E\ (e^{\pm}) = E_\gamma - 2\,m_0 c^2 \tag{3.63}$$

in accordance with a distribution extending from 0 to $E\ (e^{\pm})$ for each of the two particles (e.g. decay of the first excited level of ^{22}Na).

The internal pair creation coefficient is defined by :

$$\alpha_\pi = \frac{N_{e^{\pm}}}{N_\gamma} \tag{3.64}$$

where $N_{e^{\pm}}$ is the number of created electron-positron pairs and N_γ the number of emitted photons.

α_π is typically of the order of $10^{-4} - 10^{-3}$.

3.3.4 Multipolarity

Quantum theory permits a classification of γ transitions into multiple order transitions. This order is a function of the orbital angular momentum, of quantum number L, carried off by the photon during the transition. If $L = 0$, the transition is called 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 of the γ transition, the vectorial relationship between the angular momenta imposes the relation :

$$|J_i - J_f| \leq L \leq |J_i + J_f| \tag{3.65}$$

In fact, more often $L = |J_i - J_f|$, can be, in some cases, in competition with $L = |J_i - J_f| + 1$, and more rarely with $L = |J_i - J_f| + 2$. Moreover, the angular momentum carried off by the photon cannot be zero, consequently a $0 \rightarrow 0$ transition cannot occur except by internal conversion or by internal pair creation.

Furthermore, γ radiation is divided into “electric” and “magnetic” radiations.

For “electric” radiation, i.e. emitted by the oscillation of electrical charges, the parity change is $(-1)^L$.

For “magnetic” radiation, caused by the magnetic moment of the nucleus, the parity change is $(-1)^{(L+1)}$.

A γ transition can be a mixture of two (or more rarely three) multipole transitions. In order to conserve parity, two transitions in competition will have the multiple order 2^L and 2^{L+1}, one electric and the other one magnetic, or inversely (e.g. mixture of M1 + E2).

Expression (3.65) implies that a transition with $J_i = 0$ or $J_f = 0$ has no possible mixture. Note also that for a $J_f = J_i$ transition without parity change, a monopole transition E0 can be in competition with the mixture M1 + E2.

The classification of γ transitions and their possible mixtures is established as follows :

$L = \lvert J_i - J_f \rvert$	$\pi_f/\pi_i = -1$		$\pi_f/\pi_i = +1$	
	Transition	Possible mixture	Transition	Possible mixture
0 ($0 \to 0$)	Forbidden		Forbidden	
0 ($1/2 \to 1/2$)	E1		M1	
0 ($1 \to 1$)	E1	M2	M1	E2
1	E1	M2	M1	E2
2	M2	E3	E2	M3
3	E3	M4	M3	E4
4	M4	E5	E4	M5
even L (J_i or $J_f = 0$)	ML		EL	
odd L (J_i or $J_f = 0$)	EL		ML	

The mixture is characterized, e.g. M1 + E2, by δ^2 = E2/M1 which is the ratio of the probability of the E2 transition to that of the M1 transition [19].

3.3.5 Mean life times of excited levels

The mean life times of γ transitions are a function of the energy, the atomic number and the multipolarity. They range from 10^{-14} seconds to several years for certain M4 and E5 low energy transitions.

On the basis of the simple theory of the shell model, Weisskopf [20] calculated the probability λ per unit time (transition rate) for each type of transition. The mean life time $\tau = 1/\lambda$ decreases with $(E_\gamma)^{2L+1}$.

Moreover, for the same energy and atomic number, and the same multipole order, we have the relationship :

$$\frac{\tau_{elec}}{\tau_{magn}} \simeq 2 \times A^{2/3} \tag{3.66}$$

In fact, owing to the simplicity of the adopted model, the experimental values deviate substantially from calculated values in most cases. However, in view of the cumulative results [21], it may be considered that if :

$(T_{1/2})_{exp}/[(T_{1/2})_{cal}]_{M1}$ (M1) $< 0{,}1$	the transition is not M1
$(T_{1/2})_{exp}/[(T_{1/2})_{cal}]_{M2}$ (M2) $< 1{,}0$	the transition is not M2
$(T_{1/2})_{exp}/[(T_{1/2})_{cal}]_{M3}$ (M3) $< 0{,}1$	the transition is not M3
$(T_{1/2})_{exp}/[(T_{1/2})_{cal}]_{M4}$ (M4) $< 0{,}033$	the transition is not M4
$(T_{1/2})_{exp}/[(T_{1/2})_{cal}]_{E1}$ (E1) < 100	the transition is not E1
$(T_{1/2})_{exp}/[(T_{1/2})_{cal}]_{E2}$ (E2) $< 0{,}001$	the transition is not E2
$(T_{1/2})_{exp}/[(T_{1/2})_{cal}]_{E3}$ (E3) $< 0{,}01$	the transition is not E3

3.4 Secondary phenomena accompanying nuclear transformations

Transitions are always accompanied by secondary effects of low probability which can be theoretically predicted and calculated, and which appear as emission of electrons and photons. These secondary effects are frequently masked by the main radiations or by effects induced by radiations (e.g. Compton effect), making them difficult to measure.

3.4.1 Internal bremsstrahlung accompanying β disintegration

After its emission, an electron can be slowed down in the field of the nucleus, and the bremsstrahlung energy appears in the form of a photon [22]. (This internal bremsstrahlung must be distinguished from the external bremsstrahlung occurring in the absorbent medium). The transition energy is distributed between the electron, the neutrino and the internal bremsstrahlung photon:

$$E_{\beta max} = E_\beta + E_\nu + E_{ph} \tag{3.67}$$

The spectral distribution reveals a significant decrease in bremsstrahlung photons with their energy. The ratio of the emission probabilities for photons and β particles is expressed by :

$$\frac{P_{ph}}{P_{\beta^-}} = \frac{4\ \alpha}{3\ \pi}\ \frac{1}{(\lg 2\ W_0 - \zeta)} \tag{3.68}$$

where:

α	$\simeq 1/137$	fine structure constant
W_0	:	maximum energy in $m_0\, c^2$ units
ζ	:	constant between 2,20 and 2,35 depending on the transition type

For ^{35}S and ^{32}P, this ratio is 2×10^{-5} and 2×10^{-3} respectively. Theoretical and experimental values agree to within 20 %.

3.4.2 Internal bremsstrahlung accompanying electron capture

The origin of this photon radiation is the same as that accompanying β disintegration [24]. The available energy $E_{\beta max} = Q - E_K$ for a capture in the K shell is shared between the neutrino and the bremsstrahlung photon.

As there are no external bremsstrahlung, this process is fairly easy to analyze, and theoretical and experimental results agree within less than 15 %.

The analysis of the spectrum is of great interest as it permits direct determination of the transition energy Q. The maximum energy $E_{\beta max}$, is obtained from a plot [25]:

$$\left(\frac{N\ (E)}{E}\right)^{1/2} = C\ (E_{\beta max} - E) \tag{3.69}$$

where $N(E)$ is the number of bremsstrahlung photons with energy E and C is a constant.

The ratio of the number of emitted internal bremsstrahlung quanta and the number of K-capture events is given by [26]:

$$\frac{N_{ph}}{N_K} = 2 \times 10^{-4} \left(\frac{E_{\beta max}}{m_0\ c^2} \right)^2 f\ (Z) \tag{3.70}$$

where $f(Z)$ decreases from 0,9 to 0,3 when Z increases from 4 to 68.

For ^{55}Fe, this ratio is 3×10^{-5}.

3.4.3 Internal ionization and excitation accompanying β decay

This process is attributed to the sudden change in the nuclear charge during β decay [27]. In internal ionization, it appears by the simultaneous emission of a β particle, a neutrino and an atomic shell electron, with the following energy relationship:

$$E_{\beta max} = E_\beta + E_\nu + E_e + E_X \tag{3.71}$$

where :

$E_{\beta max}$:	maximum β-transition energy
E_β, E_ν, E_e :	energies of the three emitted particles
E_X :	binding energy of the shell (or subshell) from which the electron is emitted

The internal excitation is produced by the electron transition to an unoccupied state of a less bound shell.

The ionization and internal excitation in the K shell are best known. They are accompanied by the creation of a vacancy; the resulting emission of a X_K photon or a K-Auger electron makes the phenomenon measurable.

The internal ionization probability in the K shell is roughly proportional to Z^{-2}, going from 3×10^{-3} for ^{32}P to 1×10^{-4} for ^{204}Tl. Theoretical and experimental results agree within about 15%.

3.4.4 Internal ionization and excitation accompanying electron capture

When an atom disintegrates by electron capture in the K shell, a double vacancy can be created [28,29]. The second electron can be ejected from the atom (internal ionization or shake-off) or can undergo a transition to an unoccupied state of a less bound shell (internal excitation or shake-in). The process occurs before the rearrangement of the orbital electrons. In the case of internal ionization, the transition energy, decreased by the binding energy, is shared between the neutrino and the ejected electron.

The probability P_{KK} for the formation of a double K-shell vacancy is of the order of $0{,}18\, Z^{-2}$, while that for the electron ejection is of the order of $0{,}08\, Z^{-2}$.

In case of ^{55}Fe, the total probability for double vacancies in the K shell was measured to be $1{,}3 \times 10^{-4}$ [75].

3.4.5 Other processes

It is also worth mentioning the secondary phenomena of very low probability occurring during a γ transition [30] such as the creation of monoenergetic positron, double photon emission, double γ-e emission, double internal conversion.

3.5 Electron rearrangement

Electron capture and internal conversion (as well as the ionization and internal excitation which can be ignored in the following considerations) are processes giving rise to vacancies in the electron cloud. The filling of a vacancy is accompanied by the emission of an X-ray or an Auger electron, creating new vacancies in the less bound shells. The initial vacancy is thus transferred by cascade to the peripheral shell. The energy liberated corresponds to the binding energy of the electron in the shell in which the initial vacancy was produced.

3.5.1 K shell

Vacancies in the K shell

The probability for K vacancies created during an electron capture transition with probability P_ϵ, is: $P_\epsilon\, P_K$ (P_K: probability for the formation of a vacancy in the K shell).

The probability for K vacancies created during an electron conversion process of a γ transition with the probability P_g is: $P_g\ \dfrac{\alpha_K}{1+\alpha_t}$.

For a given radionuclide, the total number of K vacancies created, following one disintegration of the initial nuclide, is as follows, taking account of all transitions:

$$n_K = \sum P_\epsilon\ P_K + \sum P_g\ \frac{\alpha_K}{1+\alpha_t} \tag{3.72}$$

K-shell fluorescence yield

The K shell has no subshells. The K-shell fluorescence yield ω_K is the probability that the filling of a vacancy in the K shell is accompanied by a X_K radiation, $0 \le \omega_K \le 1$.

$$\omega_K = \frac{n_{X_K}}{n_{X_K} + n_{A_K}} = \frac{P_{X_K}}{P_{X_K} + P_{A_K}} \tag{3.73}$$

where:
n_{X_K}: number of X_K quanta
n_{A_K}: number of K-Auger electrons
P_{X_K}: emission probability for X_K quanta
P_{A_K}: emission probability for K-Auger electrons

The K-Auger yield is derived from the fluorescence yield:

$$a_K = 1 - \omega_K \tag{3.74}$$

as well as the number of X_K rays and Auger electrons is:

$$P_{X_K} = \omega_K (P_{X_K} + P_{A_K}) = \omega_K\, n_K \tag{3.75}$$

$$P_{A_K} = a_K (P_{X_K} + P_{A_K}) = a_K\, n_K \tag{3.76}$$

The fluorescence yield ω_K depends exclusively on the atomic number Z, except for low values of Z, where it may be influenced by the chemical state.

$\omega_K \ll 1$ for low atomic numbers. It approaches 1 for high atomic numbers.

K X-rays

The K X-ray energy emitted for a K-X transition (X= L, M, N ...) is written as:

$$E_{X_K} = E_K - E_X \tag{3.77}$$

where E_K and E_X are the binding energies of the electrons in the K and X shells respectively.

Consequently, the energy of the K X-rays is perfectly defined. They are usually classified by series, consisting of the following rays :

$$\mathrm{K}\alpha \begin{cases} \mathrm{K}\alpha_2 & \mathrm{K}-\mathrm{L}_2 \\ \mathrm{K}\alpha_1 & \mathrm{K}-\mathrm{L}_3 \end{cases}$$

$$\mathrm{K}'\beta_1 \begin{cases} \mathrm{K}\beta_3 & \mathrm{K}-\mathrm{M}_2 \\ \mathrm{K}\beta_1 & \mathrm{K}-\mathrm{M}_3 \\ \mathrm{K}\beta_5'' & \mathrm{K}-\mathrm{M}_4 \\ \mathrm{K}\beta_5' & \mathrm{K}-\mathrm{M}_5 \end{cases}$$

$$\mathrm{K}'\beta_2 \begin{cases} \mathrm{K}\beta_2 \begin{cases} \mathrm{K}\beta_2'' & \mathrm{K}-\mathrm{N}_2 \\ \mathrm{K}\beta_1' & \mathrm{K}-\mathrm{N}_3 \end{cases} \\ \mathrm{K}\beta_4 \begin{cases} \mathrm{K}\beta_4'' & \mathrm{K}-\mathrm{N}_4 \\ \mathrm{K}\beta_4' & \mathrm{K}-\mathrm{N}_5 \end{cases} \end{cases}$$

Transitions KL_1, KM_1, KN_1 are forbidden.

For $Z > 49$, it is necessary to take the KO_2 and KO_3 rays into account.

The emission probability for specific groups of K X-rays can be calculated from the total K X-ray emission probability, P_{X_K}, and from the emission probability ratios :

$$P(K_\alpha) = P_{X_K} \left[1 + \frac{P(K_\beta)}{P(K_\alpha)}\right]^{-1}$$
$$P(K_\beta) = P_{X_K} \left[1 + \frac{P(K_\alpha)}{P(K_\beta)}\right]^{-1}$$
$$P(K_{\alpha_1}) = P(K_\alpha) \left[1 + \frac{P(K_{\alpha_2})}{P(K_{\alpha_1})}\right]^{-1}$$
$$P(K_{\alpha_2}) = P(K_\alpha) \left[1 + \frac{P(K_{\alpha_1})}{P(K_{\alpha_2})}\right]^{-1}$$

The emission probability ratios $P(K_\beta)/P(K_\alpha)$ and $P(K_{\alpha_2})/P(K_{\alpha_1})$ have been measured by several authors [50]. They have also been calculated theoretically [31].

K-Auger electrons

A vacancy in the K shell is filled by an electron coming from a less bound shell. The available energy is transferred to an electron of another shell, which is also less bound. The latter electron is then ejected (Auger electron).

The energy of the K-Auger electron is:

$$E_{AK} = E_K - E_X - E_Y - \Delta E \qquad (E_Y \leq E_X) \tag{3.78}$$

where E_K, E_X, E_Y, are the binding energies of the electrons in the K-shell and in the two less bound shells (X, Y) (or subshells). ΔE is a corrective term accounting for the fact that the binding energy of the excited atom is greater than that of the atom in its ground state.

Three groups of K-Auger electrons are distinguished. Using the conventional notation we have :

- KLL-Auger electrons with six components : KL_1L_1, KL_1L_2, KL_1L_3, KL_2L_2, KL_2L_3, KL_3L_3.
- KLX-Auger electrons (X = M, N...) with the following components : KL_1M_1, KL_1M_2, KL_1M_3, $KL_1M_{4,5}$, KL_2M_1, $KL_2M_{2,3}$, $KL_2M_{4,5}$, KL_3M_1, $KL_3M_{4,5}$, KL_1N, KL_2N, KL_3N.
- KXY-Auger electrons (X = M, N...; Y = M, N...). The KXY-Auger electron spectrum is highly structured and the components are not be listed here.

As the KLL-Auger electrons are the most intense, the emission probability P_{A_K} is often written in the following form, with $\dfrac{P_{A_{KLX}}}{P_{A_{KLL}}} = \dfrac{KLX}{KLL}$:

$$P_{A_K} = KLL\left(1 + \frac{KLX}{KLL} + \frac{KXY}{KLL}\right) \tag{3.79}$$

3.5.2 L shell

Vacancies created in the L shell

The vacancies created in the L shell can have several origins :

- electron capture in the L shell. For an electron capture transition with a probability P_ϵ, the vacancy number is : $P_\epsilon P_L$;
- internal conversion in the L shell. For a γ transition with a probability $P_g = P_\gamma + P_{ce}$, the vacancy number is : $P_g\,\alpha_L/(1+\alpha_t)$;
- rearrangement following a K vacancy giving rise to a K $\rightarrow$ L vacancy transfer.

For a given radionuclide, the total number of L vacancies created per disintegration is written as follows, accounting for all transitions by electron capture, all γ transitions, and all K $\rightarrow$ L vacancy transfers :

$$n_L = n_{L_1} + n_{L_2} + n_{L_3} = \sum P_\epsilon\ P_L + \sum P_g\ \frac{\alpha_L}{1+\alpha_t} + n_K\ n_{KL} \tag{3.80}$$

where :

n_K : is the total number of K vacancies calculated by equation (3.72)

n_{KL} : is the total number of L vacancies created by K $\rightarrow$ L vacancy transfers when one K vacancy is filled.

This vacancy transfer arises from the X_K emission ($K\alpha_1$ and $K\alpha_2$ rays) and from the emission of K-Auger electrons (KLL and KLX), with $P_{X_{K\alpha}} = K\alpha$, P(KLL) = KLL, etc. :

$$n_{KL} = \omega_K\ \frac{K\alpha}{K\alpha + K\beta} + (1-\omega_K)\ \frac{2KLL + KLX}{KLL + KLX + KXY} \tag{3.81}$$

it may also be written as :

$$n_{KL} = \omega_K\ \frac{1}{1+\frac{K\beta}{K\alpha}} + (1-\omega_K)\ \frac{2+\frac{KLX}{KLL}}{1+\frac{KLX}{KLL}+\frac{KLY}{KLL}} \tag{3.82}$$

L-shell fluorescence yields

For a L_i subshell (i = 1, 2, 3), this is the probability that the filling of a L_i vacancy is accompanied by the emission of a L_i X-ray.

This leads to the definition of three L-fluorescence yields ω_{L1}, ω_{L2}, ω_{L3} :

$$\omega_{Li} = \frac{P_{X_{Li}}}{n_{Li}} \quad (i = 1, 2, 3) \tag{3.83}$$

ω_{L1}, ω_{L2} and ω_{L3}, like ω_K, depend exclusively on the atomic number Z.

n_{Li} is the number of vacancies created in the L_i subshell for one disintegration of the parent nuclide, and $P_{X_{Li}}$ is the emission probability for X_{Li} quanta.

L X-rays

The filling of a vacancy in the L shell by an electron coming from a less bound shell X (X = M, N...) can be accompanied by the emission of X_L radiation of energy $E_{X_L} = E_L - E_X$, E_L and E_X being the binding energies of the L and X shells (or subshells). The X_L series consists of the following main rays:

L_ℓ	ℓ	L_3–M_1
L_α	α_2	L_3–M_4
	α_1	L_3–M_5
L_η	η	L_2–M_1
L_β	β_6	L_3–N_1
	β_4	L_1–M_2
	β_3	L_1–M_3
	β_{10}	L_1–M_4
	β_9	L_1–M_5
	β_1	L_2–M_4
	β_2	L_3–N_5
	β_{15}	L_3–N_4
	β_7	L_3–O_1
	β_5	L_3–$O_{4,\,5}$
L_γ	γ_2	L_1–N_2
	γ_3	L_1–N_3
	γ_4	L_1–$O_{2,\,3}$
	γ_5	L_2–N_1
	γ_1	L_2–N_4
	γ_6	L_2–O_4

L-Auger electrons

A vacancy in the L shell is filled by an electron coming from a less bound shell (M, N, ...). The available energy is transferred to an electron of another less bound shell (M, N, ...). The latter electron is then ejected (L-Auger electron).

The Auger yield a_{Li} is the probability that a vacancy in the i^{th} shell is filled with an electron from a higher shell and is accompagnied by the ejection of another less-bound electron. The L-Auger electron spectrum includes a large number of lines, which are practically indistinguishable.

Coster-Kronig transitions

A Coster-Kronig transition is a special type of Auger effect, it occurs when an L_i vacancy (i = 1, 2) moves from a subshell towards another less bound subshell, $L_1 \rightarrow L_2$, $L_1 \rightarrow L_3$, $L_2 \rightarrow L_3$ [32]. The ratio of the number of vacancies filled by Coster-Kronig transitions to the total number of initial vacancies in the given subshell, respectively f_{12}, f_{13} and f_{23}, are called Coster-Kronig yields.

A transition of this type is accompanied by the emission of an L_iL_jX – Auger electron emitted from a less bound shell (X = M, N ...). It carries off the energy :

$$E_{CK} \simeq E_{L_i} - E_{L_j} - E_X \quad (i = 1{,}2 \quad j = 2{,}3) \tag{3.84}$$

This emission, which occurs before the L_i subshell is filled, has the effect of increasing the number of L vacancies.

The new vacancies V_{L_1}, V_{L_2} and V_{L_3} are such that :

$$V_{L_1} + V_{L_2} + V_{L_3} > N_{L_1} + N_{L_2} + N_{L_3} \tag{3.85}$$

where N_{L_i} is the number of primary vacancies. The V_{L_i} are calculated by the following equations :

$$V_{L_1} = N_{L_1} \tag{3.86}$$

$$V_{L_2} = N_{L_2} + f_{12}N_{L_1} \tag{3.87}$$

$$V_{L_3} = N_{L_3} + f_{13}N_{L_1} + f_{23}(N_{L_2} + f_{12}N_{L_1}) \tag{3.88}$$

These expressions require that the initial vacancy distribution is given relatively to the total number of primary vacancies in the L shell :

$$N_L = N_{L_1} + N_{L_2} + N_{L_3} = 1 \tag{3.89}$$

hence:

$$V_{L_1} + V_{L_2} + V_{L_3} > 1 \tag{3.90}$$

Mean L-fluorescence yield

The mean fluorescence yield $\bar{\omega}_L$ is derived from the three individual fluorescence yields ω_{L1}, ω_{L2} and ω_{L3}, and from the distribution of vacancies modified by the Coster-Kronig transitions.

$$\bar{\omega}_L = V_{L_1}\omega_{L1} + V_{L_2}\omega_{L2} + V_{L_3}\omega_{L3} \tag{3.91}$$

$\bar{\omega}_L$ can also be expressed as a function of primary vacancies:

$$\bar{\omega}_L = N_{L_1}[\omega_{L1} + f_{12}\ \omega_{L2} + (f_{13}\ + f_{12}\, f_{23})\omega_{L3}] + N_{L_2}\ (\omega_{L2} + f_{2\ 3}\ \omega_{L3}) + N_{L_3}\omega_{L3} \tag{3.92}$$

The L X-rays probability is given by :

$$P_{X_L} = n_L\bar{\omega}_L \tag{3.93}$$

with n_L : total number of L-shell vacancies per disintegration.

Remark : While the yields ω_{L1}, ω_{L2}, ω_{L3}, f_{12}, f_{13} and f_{23} depend exclusively on the atomic number, this in not the case for $\bar{\omega}_L$ which depends on the initial vacancies distribution, itself a function of the transitions which gave rise to it. Hence $\bar{\omega}_L$ is not constant for a given atomic number and must be measured or calculated for each radionuclide taking into account the characteristics and constants of the decay scheme.

Mean L-Auger yield

The mean L-Auger yield is derived from $\bar{\omega}_L$ for a given initial vacancy distribution, by the equation :

$$\bar{\omega}_L + \bar{a}_L = 1 \tag{3.94}$$

Where $\bar{a}_L$ is composed by, taking into account the Coster-Kronig transitions :

$\omega_{L3} + a_{L3} = 1$

$\omega_{L2} + a_{L2} + f_{23} = 1$

$\omega_{L1} + a_{L1} + f_{12} + f_{13} = 1$

And the total emission probability of the L-Auger electrons is :

$$P_{A_L} = n_L \bar{a}_L \tag{3.95}$$

With :

$P_{A_L} = P_{A_{L1}} + P_{A_{L2}} + P_{A_{L3}}$

$P_{A_{L1}} = a_{L1}\, N_{L_1} = (1 - \omega_{L1} - f_{12} - f_{13}) N_{L_1}$

$P_{A_{L2}} = a_{L2}\,(N_{L_2} + f_{12} N_{L_1}) = (1 - \omega_{L2} - f_{23})(N_{L_2} + f_{12} N_{L_1})$

$P_{A_{L3}} = a_{L3}\,(N_{L_3} + f_{13} N_{L_1} + f_{23}(N_{L_2} + f_{12} N_{L_1})) = (1 - \omega_{L3})((N_{L_3} + f_{13} N_{L_1} + f_{23}(N_{L_2} + f_{12} N_{L_1}))$

Where $P_{A_{Li}}$ are the number of Li Auger electrons.

Radiations accompanying a gamma transition

As an example of the effects of secondary phenomena accompanying the nuclear transformations, the expressions for the emission probabilities of gamma rays, conversion electrons, Auger electrons and X-ray quanta are given below for a gamma transition with the transition probability P_g and the conversion coefficients α_K, α_L, α_M and α_t. If the vacancy transfer from the K to the L and from the L to the M shell are taken into account by the vacancy transfer coefficients n_{KL} and $\bar{n}_{LM}$, the expressions for the emission probabilities are given by :

$P_\gamma = (1 - \alpha')\, P_g$

$P_{ce} = \alpha'_t\, P_g$

$P_{X_K} = \alpha'_K\, \omega_K\, P_g$

$P_{A_K} = \alpha'_K\,(1 - \omega_K)\, P_g$

$P_{X_L} = (\alpha'_K n_{KL} + \alpha'_L)\, \bar{\omega}_L\, P_g$

$P_{A_L} = (\alpha'_K n_{KL} + \alpha'_L)\,(1 - \bar{\omega}_L)\, P_g$

$P_{X_M} = (\alpha'_K n_{KL} \bar{n}_{LM} + \alpha'_L \bar{n}_{LM}) + \alpha'_M)\, \bar{\omega}_L\, P_g$

$P_{A_M} = (\alpha'_K n_{KL} \bar{n}_{LM} + \alpha'_L \bar{n}_{LM}) + \alpha'_M)(1 - \bar{\omega}_M)\, P_g$

In these equations ω_K, $\bar{\omega}_L$, $\bar{\omega}_M$, are the K-shell, the mean L-shell and the mean M-shell fluorescence yields and $\alpha'_i = \alpha_i/(1+\alpha_t)$ are the reduced conversion coefficients (i = K, L, M, t). The equations containing $\bar{\omega}_L$, $\bar{\omega}_M$, are approximations. A more detailed description would require taking into account the processes occurring in the subshells. As the data necessary for this are usually known with less accuracy there is often no advantage in comparison to the use of the above approximations. If there are several transitions, each contributes to the emission of X-ray quanta and Auger electrons and the contributions have to be summed up when the total emission probabilities characterizing the disintegration of the studied nuclide are calculated.

Chapter 4

INTERACTION OF RADIATIONS WITH MATTER

This subject, for which the reader is advised to refer to basic texts [33, 34], is raised only for two phenomena which occur in the vicinity of the radioactive source, and which have a direct effect on the probability of the radiations detected.

4.1 External bremsstrahlung

The external bremsstrahlung radiation is derived from the slowing down of electrons in the Coulomb field of nuclei in the absorbing medium surrounding the β-emitting source. The average energy of this photon radiation is about $1{,}4 \times 10^{-4}\ Z\,E_{max}^2$, where E_{max} is the maximum energy of the β radiation, provided that it is totally absorbed in the material with atomic number Z (thick source).

The energy spectrum of this bremsstrahlung extends from 0 to E_{max} and decreases very roughly as $1/E$. Since the intensity of this radiation is a function of the thickness and nature of the material crossed, it is impossible to account for it in the tables. However, its influence on some γ and X-ray spectra can be assessed.

4.2 Annihilation-in-Flight of Positrons

A positron can annihilate with an electron of the traversed medium before a complete slowing down. The two emitted photons have energies different from $m_0\,c^2$ as obtained from annihilation at rest. In γ-ray spectrometry, this phenomenon has the effect of removing, from the 511 keV peak, a fraction of the annihilation photons, the magnitude of this effect depends on the material in which the β^+ are stopped. To take this effect into account the energy of this line is given as 511, keV without uncertainty as the energy is not exactly 511 keV ; and its probability is corrected by 0,990 (3), the uncertainty of 0,3% covers most cases.

Chapter 5

DOSIMETRIC DATA

Administration of a radiopharmaceutical leads to the irradiation of various organs and tissues, which means that a prior estimate of the absorbed doses delivered to these parts of the body is necessary in order to evaluate the risks run by the individual concerned. These dose values are determined by physical and biological parameters and calculated from a computing model established by the "Medical Internal Radiation Dose Committee" (MIRD, [35]), of the American Society of Nuclear Medicine. This model is based on the concepts of target region, in which the mean absorbed dose $\overline{D}$ is estimated, as well as the source region from which the radiation arises.

The basic equation used for the calculations is [ICRU Report 32] :

$$\overline{D}(r_k \leftarrow r_h) = \widetilde{A_h} \sum_i \Delta_i \frac{\varphi_i(r_k \leftarrow r_h)}{m_k} \tag{5.1}$$

where:

$\widetilde{A_h}$ is the total number of nuclear transformations undergone by the radionuclide in the source region r_h (which denotes a volume) during the time interval considered (which may be infinite). $\widetilde{A_h}$ depends on the physical half-life of the radionuclide and on the activity administered, as well as on biological parameters relative to the distribution in time of the radionuclide within the source region ;

m_k is the mass of the target region r_k

Δ_i is the mean energy of i-type particles emitted by nuclear transformations of the radionuclide in question ; it is obtained from the expression :

$$\Delta_i = n_i \, E_i \tag{5.2}$$

with :

n_i: the mean number of i-type particles emitted per nuclear transformation of the radionuclide.

E_i: the mean energy (other than the rest energy) of i-type particle.

$\varphi_i(r_k \leftarrow r_h)$, absorbed fraction, is the fraction of the energy E_i, of each particle emitted in the source region r_h, which is given, in mean, to the target region r_k.

A special case is that where the regions r_k and r_h are identical, exactly homogeneous, of constant density and in which the radionuclide is uniformly distributed. The general

expression then reduces to the simplified form :

$$D_{eq} = \widetilde{C} \sum_i \Delta_i \tag{5.3}$$

where :

D_{eq} is the equilibrium dose,

$\widetilde{C} = \widetilde{A}/m$ the cumulated activity per unit mass.

In this case the equilibrium results from the fact that at each point of the region the energy emitted is equal to that imparted to the medium.

The purely physical data considered in this Table and needed for calculations from the general expression (5.1) are :

- the radionuclide half-life, one of the parameters involved in $\widetilde{A_h}$,
- n_i, mean number of i-type particles per nuclear transformation,
- E_i, mean energy of each i-type particle,
- Δ_i, product of n_i and E_i .

The units of the various terms of equations (5.1) and (5.2) are given in the table below:

Term	SI Unit [36]	Old unit and value in SI
$\overline{D}$	Gy	1 rad = 10^{-2} Gy
$\widetilde{A_h}$	Bq.s = 1	1 μCi.h = 1,332 $\times 10^{8}$ Bq.s
m_k	kg	1 g = 10^{-3} kg
n_i	$Bq^{-1}.s^{-1}$	1 g.rad.$\mu Ci^{-1}.h^{-1}.MeV^{-1}$ = 1/2,134
E_i	J	1MeV = 1,602 2 $\times 10^{-13}$ J
Δ_i	$J.Bq^{-1}.s^{-1}$	1 g.rad.$\mu Ci^{-1}.h^{-1} \simeq$ 7,507 $\times 10^{-14}$ J
φ_i	1	1

Chapter 6

RULES FOR EVALUATION AND COMPILATIONS

Two main groups of data sources are used to obtain the recommended data :

- specific values evaluated from all available original publications (for example : half-life),
- compiled data already evaluated by specialists (for example : Q-values), if a new experimental value exists, it may be taken into account. In this case, the corresponding reference is mentioned in the reference list of this radionuclide.

6.1 Rules for evaluation

All intermediate stages in the compilation and evaluation of a decay parameter are not presented in detail in order to avoid unnecessary complexity. The main stages comprise the following:

- critical analysis of published results and, if necessary, correction of these results to account for more recent values hitherto unavailable to the original experimentalists; as a rule, results without associated uncertainties are discarded, and the rejection of values is documented;
- data obtained through private communications are only used when all of the necessary information has been provided directly by the scientist carrying out the measurements;
- adjustments may be made to the reported uncertainties;
- recommended values are derived from an analysis of all available measurements (or theoretical considerations), along with the standard deviations corresponding to the 1 σ confidence level.

6.1.1 Evaluation of uncertainties

Definitions by the "Guide to the expression of uncertainty in measurement" [64]:

Uncertainty (of measurement) : a parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

Standard uncertainty : uncertainty of the result of a measurement expressed as a standard deviation.

Type A evaluation (of uncertainty) : method of evaluation of uncertainty by the statistical analysis of a series of observations.

Type B evaluation (of uncertainty) : method of evaluation of uncertainty by means other than the statistical analysis of a series of observations.

The uncertainties given by authors are re-evaluated by combining the standard uncertainties σ_{A} and σ_{B} by using the general law of variance propagation :

$$u_c = \sqrt{\sigma_A^2 + \sigma_B^2} \tag{6.1}$$

where : u_c : combined standard uncertainty
σ_A : type A standard deviation
σ_B : type B standard uncertainty

When the authors give insufficient information about their uncertainty calculations, the combined uncertainty u_c, may be estimated by the evaluator, based on his knowledge of the measurement method(s).

6.1.2 Determination of the best value and of the associated uncertainty.

Statistical rejection of data

The rejection of data is based on the Chauvenet's criterion [85, 86] that identifies statistical outliers. A measured value a_i is identified as outlier if :

$$\mid \bar{a} - a_i \mid > ps \tag{6.2}$$

where $\bar{a}$ is the arithmetical mean, $s^2 = \sum_i (a_i - \bar{a})^2/(n-1)$ is the sample variance, $p = 0{,}91772 + 1{,}0168 \lg n$, and n is the number of measured values.

Case of results obtained by one author using one method :

In this case the procedure is normally carried out by the author himself. Sometimes only the final result, for the mean value and the combined standard uncertainty, is given in the original publication. If details are known, the procedure is the following :

If there are n individual values a_i $(i = 1 \cdots n)$, the best value is the arithmetical mean :

$$\bar{a} = \sum_{i=1}^{n} \frac{a_i}{n} \tag{6.3}$$

with type A standard deviation :

$$\sigma_A(\bar{a}) = \left[\frac{\sum_i (a_i - \bar{a})^2}{n(n-1)} \right]^{1/2} \tag{6.4}$$

If there are m contributions σ_{Bj} $(\mathrm{j} = 1 \cdots \mathrm{k})$ to the type B standard uncertainty that are independent of each other :

$$\sigma_B(\bar{a}) = \Big[\sum_{j=1}^{m} \sigma_{Bj}^2\Big]^{1/2} \tag{6.5}$$

Combined standard uncertainty is :

$$u_c(\bar{a}) = \sqrt{\sigma_A^2(\bar{a}) + \sigma_B^2(\bar{a})} \tag{6.6}$$

Recommended value is :

$$a = \bar{a} \pm u_c(\bar{a}) \tag{6.7}$$

Case of results obtained by several authors employing the same method :

For n individual values $\bar{a}_i$ $(i = 1 \cdots n)$ having a standard deviation σ_{Ai} and a type B uncertainty σ_{Bi} the best value is obtained by taking the mean weighted by the inverse of the variances.

$$\bar{\bar{a}} = \frac{\sum_j (\bar{a}_j/\sigma_{Ai}^2)}{\sum_j (1/\sigma_{Ai}^2)} \tag{6.8}$$

The associated values u_c, σ_A, σ_B are :

$$\sigma_A(\bar{\bar{a}}) = \Big[\sum_i (1/\sigma_{Ai}^2)\Big]^{-1/2} \tag{6.9}$$

$\sigma_B(\bar{\bar{a}}) = \sum_i (\sigma_{Bi})_{min}$ or $\sigma_B(\bar{\bar{a}}) = \sqrt{\sum_i (\sigma_{Bi})_{min}^2}$ or $\sigma_B(\bar{\bar{a}}) = (\sigma_B)_{min}$
depending on the individual case. However, $\sigma_B(\bar{\bar{a}})$ cannot be less than the smallest σ_{Bi}.

Finally σ_A and σ_B are combined quadratically :

$$u_c(\bar{\bar{a}}) = \sqrt{\sigma_A^2(\bar{\bar{a}}) + \sigma_B^2(\bar{\bar{a}})} \tag{6.10}$$

The recommended value is :

$$a = \bar{\bar{a}} \pm u_c(\bar{\bar{a}}) \tag{6.11}$$

Case of results obtained by different methods :

When different measurement techniques have been applied, a weighted average is calculated using the combined uncertainties of the individual values as weights.

For n independent values a_i, each with a combined standard uncertainty u_{c_i} ; a weight p_i proportional to the inverse of the square of the individual u_{c_i} can be assigned to each value.

$$a_w = \frac{\sum\limits_{i=1}^{n} p_i\, a_i}{\sum\limits_{i=1}^{n} p_i} \tag{6.12}$$

where the weights are $p_i = 1/u_{c_i}^2$.

An internal and an external uncertainty can be assigned to the mean value [59][60] :

$$\sigma_{int}(a_w) = \left[\sum_i (1/u_{c_i}^2)\right]^{-1/2} \tag{6.13}$$

The internal variance $\sigma_{int}^2(a_w)$ is the expected uncertainty of the mean, based on the individual *a priori* variances $u_{c_i}^2$ (by uncertainty propagation).

The external uncertainty is also calculated :

$$\sigma_{ext}(a_w) = \left[\frac{\sum (a_i - a_w)^2/u_{c_i}^2}{(n-1)\sum(1/u_{c_i}^2)}\right]^{1/2} \tag{6.14}$$

The external variance $\sigma_{ext}^2(a_w)$ includes the scatter of the data and is based on the amount by which each a_i deviates from the mean when measured as a fraction of its given uncertainty u_{c_i}.

A measure of the consistency of the data is given by the ratio [59, 60]:

$$\sigma_{ext}/\sigma_{int} = \sqrt{\chi^2/(n-1)} \tag{6.15}$$

If this ratio is significantly greater than unit, at least one of the input data most probably has an underestimated u_{c_i} which should be increased.

A critical value of $\chi^2/(n-1)$ at 1% confidence level is used as a practical test for discrepant data. The following table lists critical values of $\chi^2/(n-1)$(critical) for an increasing degree of freedom $\nu = N - 1$. [84]

ν	$\chi^2/(n-1)$(critical)	ν	$\chi^2/(n-1)$(critical)
1	6,6	12	2,2
2	4,6	13	2,1
3	3,8	14	2,1
4	3,3	15	2,0
5	3,0	16	2,0
6	2,8	17	2,0
7	2,6	18 - 21	1,9
8	2,5	22 - 26	1,8
9	2,4	27 - 30	1,7
10	2,3	>30	$1 + 2{,}33\sqrt{2/\nu}$
11	2,2		

If $\chi^2/(n-1) \leq$ *critical* $\chi^2/(n-1)$ the recommended value is given by:

$$a = a_w \pm \sigma_{int}(a_w) \tag{6.16}$$

If $1 < \chi^2/(n-1) >$ *critical* $\chi^2/(n-1)$, the method of limitation of the relative statistical weight [60, 61] is recommended when there are three or more values ; uncertainty of a value

contributing more than 50 % to the total weight is increased to reduce its contribution to 50 %. The weighted and unweighted average and $critical \chi^2/(n-1)$ are then recalculated:

If $\chi^2/(n-1) \leq critical\ \chi^2/(n-1)$ the recommended value is given by :

$$a = a_w \pm (\text{the larger of } : \sigma_{int}(a_w) \text{ and } \sigma_{ext}(a_w)) \tag{6.17}$$

If $\chi^2/(n-1) > critical\ \chi^2/(n-1)$, the weighted or unweighted mean is chosen, depending on whether or not the uncertainties of the average values make them overlap with each other. If overlap occurs, the weighted average is recommended ; otherwise the unweighted average is chosen. In either case, the uncertainty can be increased to cover the most accurate value.

Parameters evaluated according to these procedures and rules include half-lives, energies and number of emitted particles, and some internal conversion coefficients. All remaining data given in these tables are generally taken from compilations.

6.1.3 Balanced decay schemes

All the probabilities for transitions correspond to balanced schemes and permit the formulation of a fully consistent set of values. This balance implies obvious relationships such as the following:

- sum of the transition probabilities for all the decay transitions (α , β , γ , ϵ)in the horizontal plan of a decay scheme the is equal to 1 (or 100 %). This ruling is also valid for the highest energies of the decay scheme where only β (or α , ϵ) transitions are relevant, and for the lowest levels of the decay scheme, where sometimes only γ transitions are involved;
- for an excited nuclear level, the sum of the transition probabilities feeding the level (γ, β, ...) is equal to the sum of the transition probabilities depopulating this level;
- when the relative emission probabilities $P(rel)_{\gamma_i}$ of the γ emission are known with respect to one emission such as γ_1, and no feeding to the ground state from α, β, and ϵ transitions is assumed, all the absolute emitted photon numbers for the γ emissions $\mathrm{P(abs)}_{\gamma_i}$ can be calculated from the equation:

$$P(abs)_{\gamma_i} = P(rel)_{\gamma_i} \times \frac{1}{k} \tag{6.18}$$

where k is the "normalization factor",and is determined by :

$$k \sum_i P(rel)_{\gamma_i}(1 + \alpha_{t_i}) = 1 \tag{6.19}$$

where the sum covers the γ-transitions feeding the ground state.

6.2 Compilations

6.2.1 β and electron capture transitions

Depending on the individual radionuclide, β-transition energies are either evaluated on the basis of experimental data (maximum β energies), or derived from the atomic mass differences

obtained from the tabulations of AUDI and WAPSTRA [37] and the γ-transition energies. The average β energies are generally computed [72], and the values of $\lg ft$ are calculated from the tables of GOVE and MARTIN [9], as well as ϵ/β^+ if possible.

Electron-capture transition energies are derived from the atomic mass differences and the γ-transition energies. Capture probabilities P_K, $P_L \ldots$ are calculated from equations (3.31) and (3.34) to (3.37) where the ratios of the radial wave function components of the electron [13, 14, 15], and the corrective terms for exchange $X^{L/K}$ [12, 16, 17, 18, 74] are evaluated from tables.

6.2.2 γ transitions

Internal conversion coefficients of pure transitions are evaluated and compared with theoretical values [41,42], which can be preferred if the experimental data are uncertain. The theoretical values are deduced from the tables of either RÖSEL *et al.* interpolated with a cubic spline method for $30 \leq Z \leq 104$ or BAND *et al.*. The uncertainties of these theoretical values are estimated to be 3%.

Internal conversion coefficients are calculated according to ref. [44] in order to account for penetration effects of some M1 and E2 transitions.

Internal conversion coefficients of multipole transitions (e.g.: M1 + E2) are derived from tables of theoretical data, taking the mixing ratio into account:

$$\alpha_{i(M1+E2)} = (1 - \delta^2)\ \alpha_{i(M1)} + \delta^2 \alpha_{i(E2)} \tag{6.20}$$

i = K, L1, L2, ..., T.

α_π coefficients are interpolated from theoretical values [56], and the uncertainties are assumed to be between 5% and 10%.

6.2.3 Level spins and parities

Level spins and parities are usually extracted from the Nuclear Data Sheets [45].

6.2.4 Constants of the atomic shell

The K-shell fluorescence yields ω_K and their uncertainties are taken from the evaluation of BAMBYNEK *et al.* [46, 57, 58] with uncertainties ranging from 1 % ($Z > 35$) to 10 % ($Z = 5$), and from subsequent experimental results.

Mean L-shell fluorescence yields $\bar{\omega}_L$ are taken from the evaluation of SCHÖNFELD *et al.* [50]. This evaluation includes both experimental [63,65,66] and theoretical values [67]. The relative uncertainties are ≤ 4 % (for $Z > 29$).

Mean M-shell fluorescence yields $\bar{\omega}_M$ are obtained from the fitting of experimental data by HUBBELL [66, 73].

Relative X-ray emission rates $K\beta/K\alpha$ are taken from SCHÖNFELD *et al.* [50], and the $K\alpha_1/K\alpha_2$ from the theoretical values of SCOFIELD [68]. Uncertainties are assumed to be of the order of 1 %.

X-ray radiation energies are taken from the tables of BEARDEN [51].

Relative emission probabilities of K-Auger electron groups are deduced from the X-ray ratio [50] with uncertainties of the order of 3 %.

Energies of the K and L-Auger electrons are taken from the table of LARKINS [53].

The mean number of vacancies created in the L shell (from one K hole) n_{KL} and in the M shell (from one L hole) $\bar{n}_{LM}$ are estimated from the preceding values.

6.2.5 m_0c^2 energy

The m_0c^2 energy is taken as 510,998 902 (21) keV given by the CODATA Group (2000) [54].

Chapter 7

CONTENTS OF THE TABLES

Each section devoted to a radionuclide or to a radioactive series contains the following :

- decay scheme(s),
- half-lives, Q-values, atomic shell data,
- tables of probabilities of different transitions,
- tables of probabilities of different emissions,
- major production methods,
- references employed in the evaluation,

7.1 Radioactive series

When two or more radionuclides compose a radioactive series, the nuclear and atomic data are presented separately for each. If the half-life of the daughter(s) is shorter than that of the parent, so that an equilibrium can be achieved, the emission probabilities of the different radiations are given for all the radionuclides involved. Moreover, if the half-life of the daughter is sufficiently long to permit its use after separation, it is covered by a separate section (e.g. ^{140}Ba $-^{140}$ La). This rule also applies if the daughter is an isomer (e.g. ^{125}Sb $-^{125}$ Te^{m}).

Furthermore, if a radionuclide possesses an isomer of specific interest, it is covered by a separate section (e.g. ^{58}Co^{m}, ^{60}Co^{m}).

7.2 Decay scheme

A decay scheme includes the following information :

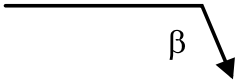
- half-lives of ground states, together with those of excited levels longer than 1×10^{-12} seconds,
- disintegration energies,
- energy, spin and parity of levels,
- transitions listed by the index : initial level, final level. The levels are arbitrarily designated by a number from 0 for the ground state to n for the nth excited level.

The transition energies are not shown on the decay schemes. The α , β and electron capture transitions probabilities are given for 100 disintegrations. The gamma emission probabilities are given following 100 disintegrations.

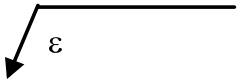
Intervals between levels are roughly proportional to energy differences.

Transitions with probabilities over 0,5 are shown by heavy lines, those between 0,05 and 0,5 in medium-thick lines, as used for the ground states. Those below 0,05 are shown by fine lines; this rule is not rigidly applied, as a transition with probability less than 0,05 is shown by a medium line if it is of special interest.

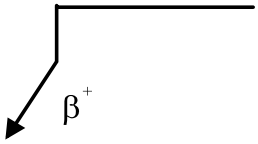
The decay scheme diagram is, as a rule, similar to that of other tables [45]



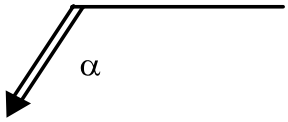
β decay.



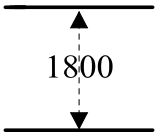
Electron capture decay.



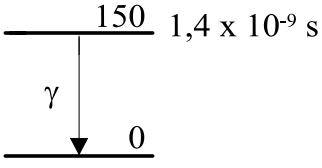
β^+ decay. The vertical line correspond to an energy $2m_0c^2$ = 1,022 MeV.



α decay.



Q values of disintegration energies, Q^- being shown on the right of the schemes, Q^+ and Q_α on the left.



The upper level has an energy of 150 keV and a half-life of 1,4 x 10^{-9} s. It is de-excited by the emission of a γ photon or an internal conversion electron.

2^+	*Spin and parity are considered as certain.*
(4^+)	*Spin and parity are uncertain.*
$(4)^+$	*Spin is uncertain, parity is considered as certain.*
$2^{(+)}$	*Parity is uncertain, spin is considered as certain.*
$(3/2, 1/2)^-$	*Parity is considered as certain, and one of the spins as certain.*

7.3 Tables

7.3.1 Notation

Following the Guide to the expression of uncertainty in measurement [64], the values and their uncertainties are reported as :

$$E = 100{,}021\,47\,(45)\ \text{keV}$$

where the number in parentheses is the numerical value of the combined standard uncertainty u_c referred to the corresponding last digits of the quoted result.

7.3.2 Nuclear data

The nuclear data comprise the following :

- the half-life of the radionuclide and those of the daughter radionuclides,
- disintegration energies,
- α transitions, β transitions and electron capture transitions are given in order of increasing energy. The first column designates the transition. The remaining columns indicate the energy, the transition probability, the α transition hindrance factor, the nature, the lg ft for β transitions and, for electron capture transitions, the probabilities P_{ϵ_K}, P_{ϵ_L}, P_{ϵ_M} of capture in the atomic shells.

– γ transitions are also given by order of increasing energy. The first column designates the transition. The remaining columns indicate the energy, probability, multipolarity, internal conversion coefficients α_{K}, α_{L}, the total conversion coefficient α_{t} and, occasionally, the coefficient of creation of the internal pair α_{π}.

Remarks:

A multipolarity such as M1 (+ E2) indicates that the percentage of E2 is very low or is uncertain.

A multipolarity such as M1 or E2 indicates a pure γ transition of one type.

7.3.3 Atomic shell data

Atomic shell data include the following:

– fluorescence yields ω_K, $\bar{\omega}_L$, $\bar{\omega}_M$, n_{KL}, $\bar{n}_{LM}$,
– energies and relative probabilities of $\mathrm{X_K}$ lines,
– energies of $\mathrm{X_L}$ lines. For radionuclides with $Z \leq 52$, only the minimum and maximum energies are indicated,
– energies and relative emission probabilities of K-Auger electrons,
– minimum and maximum energies of L-Auger electrons. The minimum energy is that of the $\mathrm{L_3\,M_1\,M_1}$ etc. transition. The maximum energy is that of the $\mathrm{L_1\,M\,M}$ transition for $Z \leq 32$, of the $\mathrm{L_1\,N\,N}$ transition for $33 \leq \mathrm{Z} \leq 37$, of the $\mathrm{L_1\,N\,O}$ transition for $38 \leq \mathrm{Z} \leq 49$ and of the $\mathrm{L_1\,O\,O}$ transition for $\mathrm{Z} \geq 50$.

7.3.4 Probability for different radiations

Transition probabilities are always related to 100 nuclear transformations of the radionuclide and are given in order of increasing energy.

Isomeric transitions: when a radionuclide with half-life T_1 has an isomer daughter with half-life T_2 lower than T_1, the emission probabilities P_{γ_i} and P_{ce_i} are related to the probability P_i of the isomeric transition by:

$$P_{\gamma_i} + P_{ce_i} = \frac{T_1}{T_1 - T_2}\ P_i \left[1 - e^{-\ln 2\, \frac{T_1 - T_2}{T_1\ T_2}\ t}\right] \tag{7.1}$$

For $t \geq 10\,T_2$, the parent and daughter are practically in equilibrium:

$$P_{\gamma_i} + P_{ce_i} = \frac{T_1}{T_1 - T_2}\ \ P_i \tag{7.2}$$

Note that the isomeric transition probability P_i is the probability that the disintegration of the radionuclide will be followed by this transition. It is independent of the time and cannot exceed 1.

7.4 Main production modes

The production processes quoted are those which are most widely employed. The impurities mentioned are those generally encountered, with the exception of accidental contaminations. The cross section, given only for thermal neutron activation, is taken from the tables

of MUGHABGHAB *et al.* [55]. The useful data for activation with charged particles (cross section as a function of particle energy) may be derived from tables or publications [78].

7.5 References used

The references quoted are those which were used in the evaluations, with the extracted quantities in square brackets.

7.6 Spectra

Spectra are not given in the new computerised version of these tables [76,82,83], they can be found in the Gamma-Ray Spectrum Catalog [77].

Chapter 8

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