

## A Table of Frequently Used Radioisotopes

Only decays with the largest branching fractions are listed. For  $\beta$  emitters the maximum energies of the continuous  $\beta$ -ray spectra are given. ‘ $\rightarrow$ ’ denotes the decay to the subsequent element in the table. EC stands for ‘electron capture’, a (= annus, Latin) for years, h for hours, d for days, min for minutes, s for seconds, and ms for milliseconds.

isotope $Z$ element	decay type	half- life	$\beta$ resp. $\alpha$ energy (MeV)	$\gamma$ energy (MeV)
$^3_1\text{H}$	$\beta^-$	12.3 a	0.0186	no $\gamma$
$^7_4\text{Be}$	EC, $\gamma$	53 d	–	0.48
$^{10}_4\text{Be}$	$\beta^-$	$1.5 \times 10^6$ a	0.56	no $\gamma$
$^{14}_6\text{C}$	$\beta^-$	5730 a	0.156	no $\gamma$
$^{22}_{11}\text{Na}$	$\beta^+$ , EC	2.6 a	0.54	1.28
$^{24}_{11}\text{Na}$	$\beta^-, \gamma$	15.0 h	1.39	1.37
$^{26}_{13}\text{Al}$	$\beta^+$ , EC	$7.17 \times 10^5$ a	1.16	1.84
$^{32}_{14}\text{Si}$	$\beta^-$	172 a	0.20	no $\gamma$
$^{32}_{15}\text{P}$	$\beta^-$	14.2 d	1.71	no $\gamma$
$^{37}_{18}\text{Ar}$	EC	35 d	–	no $\gamma$
$^{40}_{19}\text{K}$	$\beta^-, \text{EC}$	$1.28 \times 10^9$ a	1.33	1.46
$^{51}_{24}\text{Cr}$	EC, $\gamma$	27.8 d	–	0.325
$^{54}_{25}\text{Mn}$	EC, $\gamma$	312 d	–	0.84
$^{55}_{26}\text{Fe}$	EC	2.73 a	–	0.006
$^{57}_{27}\text{Co}$	EC, $\gamma$	272 d	–	0.122
$^{60}_{27}\text{Co}$	$\beta^-, \gamma$	5.27 a	0.32	1.17 & 1.33
$^{66}_{31}\text{Ga}$	$\beta^+, \text{EC}, \gamma$	9.4 h	4.15	1.04
$^{68}_{31}\text{Ga}$	$\beta^-, \text{EC}, \gamma$	68 min	1.88	1.07
$^{85}_{36}\text{Kr}$	$\beta^-, \gamma$	10.8 a	0.67	0.52
$^{89}_{38}\text{Sr}$	$\beta^-$	51 d	1.49	no $\gamma$
$^{90}_{38}\text{Sr} \rightarrow$	$\beta^-$	28.7 a	0.55	no $\gamma$
$^{90}_{39}\text{Y}$	$\beta^-$	64 h	2.28	no $\gamma$
$^{99m}_{43}\text{Tc}$	$\gamma$	6 h	–	0.140

isotope ${}^A_Z \text{element}$	decay type	half- life	$\beta$ resp. $\alpha$ energy (MeV)	$\gamma$ energy (MeV)
${}^{106}_{44} \text{Ru} \rightarrow$	$\beta^-$	1.0 a	0.04	no $\gamma$
${}^{106}_{45} \text{Rh}$	$\beta^-, \gamma$	30 s	3.54	0.51
${}^{112}_{47} \text{Ag}$	$\beta^-, \gamma$	3.13 h	3.90	0.62
${}^{109}_{48} \text{Cd} \rightarrow$	EC	1.27 a	—	no $\gamma$
${}^{109m}_{47} \text{Ag}$	$\gamma$	40 s	—	0.088
${}^{113}_{50} \text{Sn}$	EC, $\gamma$	115 d	—	0.392
${}^{132}_{52} \text{Te}$	$\beta^-, \gamma$	77 h	0.22	0.23
${}^{125}_{53} \text{I}$	EC, $\gamma$	60 d	—	0.035
${}^{129}_{53} \text{I}$	$\beta^-, \gamma$	$1.6 \times 10^7$ a	0.15	0.038
${}^{131}_{53} \text{I}$	$\beta^-, \gamma$	8.05 d	0.61	0.36
${}^{133}_{54} \text{Xe}$	$\beta^-, \gamma$	5.24 d	0.35	0.08
${}^{134}_{55} \text{Cs}$	$\beta^-, \beta^+, \gamma$	2.06 a	0.65	0.61
${}^{137}_{55} \text{Cs} \rightarrow$	$\beta^-$	30 a	0.51 & 1.18	0.66
${}^{137m}_{56} \text{Ba}$	$\gamma$	2.6 min	—	0.66
${}^{133}_{56} \text{Ba}$	EC, $\gamma$	10.5 a	—	0.36
${}^{140}_{57} \text{La}$	$\beta^-, \gamma$	40.2 h	1.34	1.60
${}^{144}_{58} \text{Ce} \rightarrow$	$\beta^-, \gamma$	285 d	0.32	0.13
${}^{144}_{59} \text{Pr}$	$\beta^-, \gamma$	17.5 min	3.12	0.69
${}^{144}_{60} \text{Nd}$	$\alpha$	$2.3 \times 10^{15}$ a	1.80	no $\gamma$
${}^{152}_{63} \text{Eu}$	EC, $\beta^\mp, \gamma$	13.5 a	0.68	0.122
${}^{192}_{77} \text{Ir}$	EC, $\beta^-, \gamma$	74 d	0.67	0.32
${}^{198}_{79} \text{Au}$	$\beta^-, \gamma$	2.7 d	0.96	0.41
${}^{204}_{81} \text{Tl}$	$\beta^-, \text{EC}$	3.78 a	0.76	no $\gamma$
${}^{207}_{83} \text{Bi}$	EC, $\gamma$	31.6 a	0.48	0.57
${}^{222}_{86} \text{Rn} \rightarrow$	$\alpha, \gamma$	3.8 d	5.48	0.51
${}^{218}_{84} \text{Po} \rightarrow$	$\alpha, \beta^-$	3.1 min	$\alpha$ : 6.00	no $\gamma$
${}^{214}_{82} \text{Pb} \rightarrow$	$\beta^-, \gamma$	26.8 min	0.73	0.35
${}^{214}_{83} \text{Bi}$	$\beta^-, \gamma$	19.9 min	1.51	0.61
${}^{226}_{88} \text{Ra}$	$\alpha, \gamma$	1600 a	4.78	0.19
${}^{228}_{90} \text{Th}$	$\alpha, \gamma$	1.9 a	5.42	0.24
${}^{234}_{92} \text{U}$	$\alpha, \gamma$	$2.5 \times 10^5$ a	4.77	0.05

isotope $A_Z$ element	decay type	half-life	$\beta$ resp. $\alpha$ energy (MeV)	$\gamma$ energy (MeV)
$^{235}_{92}\text{U}$	$\alpha, \gamma$	$7.1 \times 10^8$ a	4.40	0.19
$^{238}_{92}\text{U}$	$\alpha, \gamma$	$4.5 \times 10^9$ a	4.20	0.05
$^{239}_{94}\text{Pu}$	$\alpha, \gamma$	24 110 a	5.15	0.05
$^{240}_{94}\text{Pu}$	$\alpha, \gamma$	6564 a	5.16	0.05
$^{241}_{95}\text{Am}$	$\alpha, \gamma$	432 a	5.49	0.06
$^{252}_{98}\text{Cf}$	$\alpha, \gamma$	2.6 a	6.11	0.04
$^{252}_{100}\text{Fm}$	$\alpha, \gamma$	25 h	7.05	0.096
$^{268}_{109}\text{Mt}$	$\alpha$	70 ms	10.70	–

### Explanatory note

The heavy  $\alpha$ -ray-emitting radioisotopes can also decay by spontaneous fission. Half-lives for spontaneous fission are usually rather long. More detailed information about decay modes and level diagrams can be taken from nuclear data tables. Corresponding references are listed under ‘Further Reading’ in the section ‘Tables of Isotopes and Nuclear Data Sheets’. The most recent information on the table of isotopes can be found in the Internet under

<http://atom.kaeri.re.kr/>

and

<http://isotopes.lbl.gov/education> .



## B Examples of Exemption Limits for Absolute and Specific Activities

There are no universal international values for exemption limits for radioactive sources and radioactive material. Different countries have defined limits based on the guidelines as recommended by the International Commission on Radiological Protection. The table below gives some examples which have been adopted by the new German radiation-protection ordinance in 2001. The corresponding limits in other countries are quite similar, although there are also some important differences in some national regulations.

If several sources each with activity  $A_i$  and corresponding exemption limit  $A_i^{\max}$  are handled in a laboratory, the following condition must be fulfilled:

$$\sum_{i=1}^N \frac{A_i}{A_i^{\max}} \leq 1 .$$

This prevents the acquisition of several sources each with an activity below the exemption limit thereby possibly circumventing the idea of the exemption limit.

radioisotope	exemption limit	
	activity in Bq	specific activity in Bq/g
${}^3_1\text{H}$	$10^9$	$10^6$
${}^7_4\text{Be}$	$10^7$	$10^3$
${}^{14}_6\text{C}$	$10^7$	$10^4$
${}^{24}_{11}\text{Na}$	$10^5$	10
${}^{32}_{15}\text{P}$	$10^5$	$10^3$
${}^{40}_{19}\text{K}^*$	$10^6$	$10^2$
${}^{54}_{25}\text{Mn}$	$10^6$	10
${}^{55}_{26}\text{Fe}$	$10^6$	$10^4$
${}^{57}_{27}\text{Co}$	$10^6$	$10^2$
${}^{60}_{27}\text{Co}$	$10^5$	10

radioisotope	exemption limit activity in Bq	specific activity in Bq/g
$^{82}_{35}\text{Br}$	$10^6$	10
$^{89}_{38}\text{Sr}$	$10^6$	$10^3$
$^{90}_{38}\text{Sr}^\dagger$	$10^4$	$10^2$
$^{99\text{m}}_{43}\text{Tc}$	$10^7$	$10^2$
$^{106}_{44}\text{Ru}^\dagger$	$10^5$	$10^2$
$^{110\text{m}}_{47}\text{Ag}$	$10^6$	10
$^{109}_{48}\text{Cd}^\dagger$	$10^6$	$10^4$
$^{125}_{53}\text{I}$	$10^6$	$10^3$
$^{129}_{53}\text{I}$	$10^5$	$10^2$
$^{131}_{53}\text{I}$	$10^6$	$10^2$
$^{134}_{55}\text{Cs}$	$10^4$	10
$^{137}_{55}\text{Cs}^\dagger$	$10^4$	10
$^{133}_{56}\text{Ba}$	$10^6$	$10^2$
$^{152}_{63}\text{Eu}$	$10^6$	10
$^{197}_{80}\text{Hg}$	$10^7$	$10^2$
$^{204}_{81}\text{Tl}$	$10^4$	$10^4$
$^{214}_{82}\text{Pb}$	$10^6$	$10^2$
$^{207}_{83}\text{Bi}$	$10^6$	10
$^{210}_{84}\text{Po}$	$10^4$	10
$^{220}_{86}\text{Rn}^\dagger$	$10^7$	$10^4$
$^{222}_{86}\text{Rn}^\dagger$	$10^8$	10
$^{226}_{88}\text{Ra}^\dagger$	$10^4$	10
$^{227}_{89}\text{Ac}^\dagger$	$10^3$	0.1
$^{232}_{90}\text{Th}^\dagger$	$10^4$	10
$^{233}_{92}\text{U}$	$10^4$	10
$^{235}_{92}\text{U}^\dagger$	$10^4$	10
$^{238}_{92}\text{U}^\dagger$	$10^4$	10
$^{239}_{94}\text{Pu}$	$10^4$	1
$^{240}_{94}\text{Pu}$	$10^3$	1

radioisotope	exemption limit	
	activity in Bq	specific activity in Bq/g
$^{241}_{95}\text{Am}$	$10^4$	1
$^{244}_{96}\text{Cm}$	$10^4$	10
$^{252}_{98}\text{Cf}$	$10^4$	10

\* as naturally occurring isotope unlimited

† in equilibrium with its daughter nuclei; the radiation exposure due to these daughter isotopes is taken account of in the exemption limits

## C Maximum Permitted Activity Concentrations Discharged from Radiation Areas

There are no universal international values for the limits of radioactive material that may be released from radiation areas. Different countries have defined limits based on the guidelines as recommended by the International Commission on Radiological Protection. These limits generally refer to a maximum annual dose of 0.3 mSv that people from the general public may receive from such discharges. The table below gives some examples which have been adopted by the new German radiation protection ordinance in 2001. The corresponding limits in other countries are quite similar, but do vary in some national regulations.

radioisotope	maximum permitted activity concentration	
	in air in Bq/m <sup>3</sup>	in water in Bq/m <sup>3</sup>
<sup>3</sup> H	10 <sup>2</sup>	10 <sup>7</sup>
<sup>7</sup> Be	$6 \times 10^2$	$5 \times 10^6$
<sup>14</sup> C	6	$6 \times 10^5$
<sup>24</sup> Na	90	$3 \times 10^5$
<sup>32</sup> P	1	$3 \times 10^4$
<sup>42</sup> K	$2 \times 10^2$	$2 \times 10^5$
<sup>54</sup> Mn	20	$2 \times 10^5$
<sup>55</sup> Fe	20	$10^5$
<sup>57</sup> Co	30	$3 \times 10^5$
<sup>60</sup> Co	1	$2 \times 10^4$
<sup>82</sup> Br	50	$10^5$
<sup>89</sup> Sr	4	$3 \times 10^4$
<sup>90</sup> Sr	0.1	$4 \times 10^3$

<b>radioisotope</b>	<b>maximum permitted activity concentration</b>	
	<b>in air in Bq/m<sup>3</sup></b>	<b>in water in Bq/m<sup>3</sup></b>
<sup>99m</sup> Tc <sub>43</sub>	$2 \times 10^3$	$4 \times 10^6$
<sup>106</sup> Ru <sub>44</sub>	0.6	$10^4$
<sup>110m</sup> Ag <sub>47</sub>	1	$4 \times 10^4$
<sup>109</sup> Cd <sub>48</sub>	4	$4 \times 10^4$
<sup>125</sup> I <sub>53</sub>	0.5	$2 \times 10^4$
<sup>129</sup> I <sub>53</sub>	0.03	$4 \times 10^3$
<sup>131</sup> I <sub>53</sub>	0.5	$5 \times 10^3$
<sup>134</sup> Cs <sub>55</sub>	2	$2 \times 10^4$
<sup>137</sup> Cs <sub>55</sub>	0.9	$3 \times 10^4$
<sup>133</sup> Ba <sub>56</sub>	4	$4 \times 10^4$
<sup>152</sup> Eu <sub>63</sub>	0.9	$5 \times 10^4$
<sup>197</sup> Hg <sub>80</sub>	$10^2$	$4 \times 10^5$
<sup>204</sup> Tl <sub>81</sub>	10	$7 \times 10^4$
<sup>214</sup> Pb <sub>82</sub>	2	$3 \times 10^5$
<sup>207</sup> Bi <sub>83</sub>	1	$9 \times 10^4$
<sup>210</sup> Po <sub>84</sub>	0.008	30
<sup>226</sup> Ra <sub>88</sub>	0.004	$2 \times 10^2$
<sup>227</sup> Ac <sub>89</sub>	$7 \times 10^{-5}$	30
<sup>232</sup> Th <sub>90</sub>	$3 \times 10^{-4}$	$2 \times 10^2$
<sup>233</sup> U <sub>92</sub>	0.004	$2 \times 10^3$
<sup>235</sup> U <sub>92</sub>	0.004	$3 \times 10^3$
<sup>238</sup> U <sub>92</sub>	0.005	$3 \times 10^3$
<sup>239</sup> Pu <sub>94</sub>	$3 \times 10^{-4}$	$2 \times 10^2$
<sup>240</sup> Pu <sub>94</sub>	$3 \times 10^{-4}$	$2 \times 10^2$
<sup>241</sup> Am <sub>95</sub>	$4 \times 10^{-4}$	$2 \times 10^2$
<sup>244</sup> Cm <sub>96</sub>	$6 \times 10^{-4}$	$3 \times 10^2$
<sup>252</sup> Cf <sub>98</sub>	0.002	$2 \times 10^2$
any unknown isotope mixture	$10^{-5}$	10

These limits describe maximum activity concentrations in air released from radiation areas with the danger of inhalation, and maximum permitted activity concentrations, which are allowed to be discharged as sewage water.

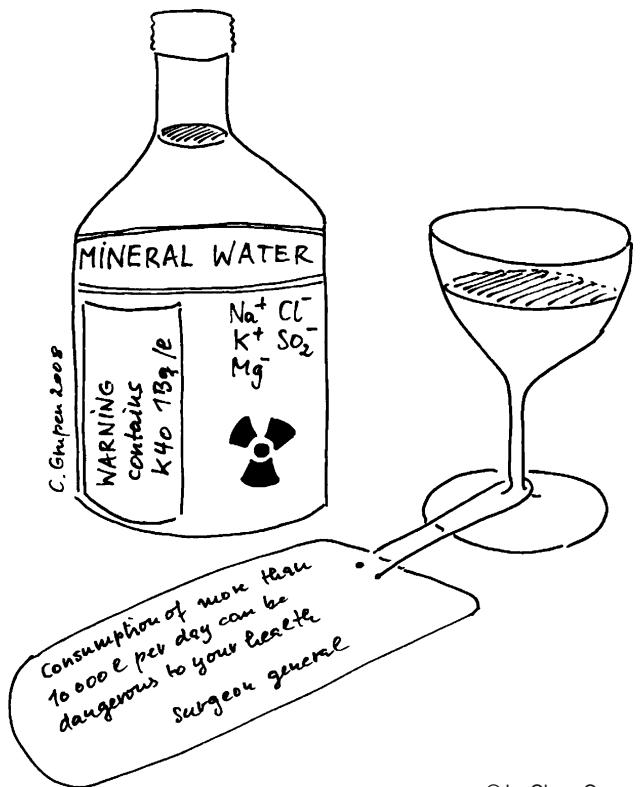
Correspondingly, the condition

$$\sum_{i=1}^N \frac{\bar{C}_{i,a}}{C_i} \leq 1$$

must be respected, where

$C_i$  is the maximum permitted activity concentration  
and

$\bar{C}_{i,a}$  the actual released average annual activity concentration.



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## Examples of Clearance Levels

There are no universal international values for clearance levels for material containing residual radioactivity. After approved clearance the material is no longer considered as radioactive. Different countries have defined limits based on the guidelines as recommended by the International Commission on Radiological Protection. Clearance can only be approved if the residual activity causes insignificant exposure to the public ( $\leq 10 \mu\text{Sv/yr}$ ). The table below gives some examples which have been adopted by the new German radiation-protection ordinance in 2001. The corresponding limits in other countries are quite similar.

radioisotope	clearance of		
	solid material, liquids (Bq/g)	construction waste, excavation residues (Bq/g)	ground area (Bq/g)
$^3\text{H}$	1000	60	3
$^{32}\text{P}$	20	20	0.02
$^{60}\text{Co}$	0.1	0.09	0.03
$^{90}\text{Sr}^*$	2	2	0.002
$^{137}\text{Cs}^*$	0.5	0.4	0.06
$^{226}\text{Ra}^*$	0.03	0.03	†
$^{232}\text{Th}$	0.03	0.03	†
$^{235}\text{U}^*$	0.5	0.3	†
$^{238}\text{U}^*$	0.6	0.4	†
$^{239}\text{Pu}$	0.04	0.08	0.04
$^{240}\text{Pu}$	0.04	0.08	0.04
$^{241}\text{Am}$	0.05	0.05	0.06

\* in equilibrium with daughter isotopes; the radiation exposure due to these daughter isotopes is taken care of in the clearance levels

† naturally occurring radioisotopes in the ground with activities around 0.01 Bq/g

## D Examples of Limits for Surface Contaminations

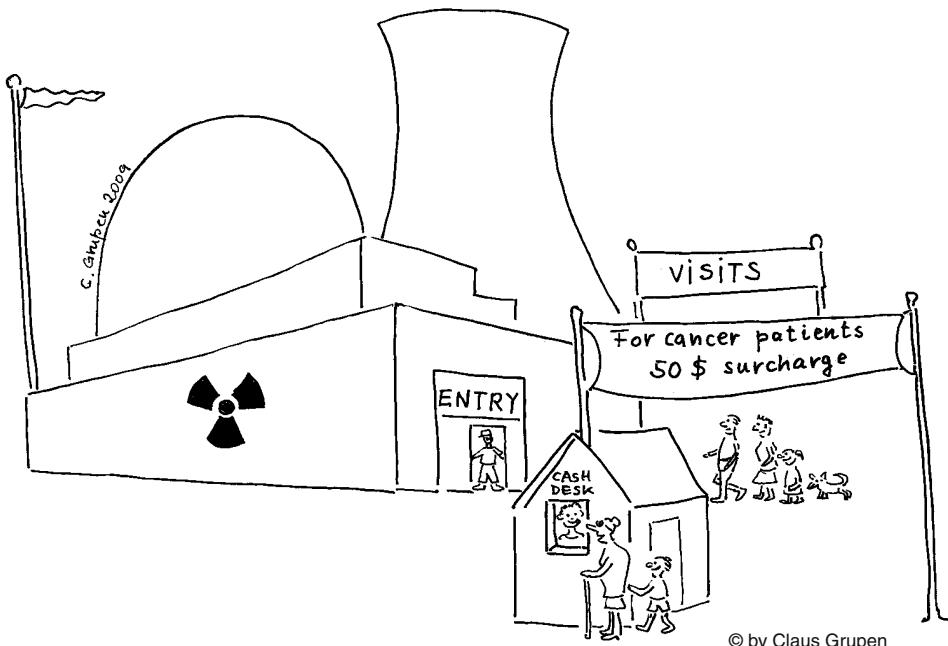
There are no universal international values for limits on surface contaminations in working areas. Because of the higher biological effectiveness the limits for  $\alpha$  particles are more stringent compared to those of  $\beta$ - and  $\gamma$ -ray emitters, usually by a factor of 10. Different countries have defined limits based on the guidelines as recommended by the International Commission on Radiological Protection. The table below gives some examples which have been adopted by the new German radiation-protection ordinance in 2001. The corresponding limits in other countries are quite similar.

radioisotope	surface contamination in $\text{Bq}/\text{cm}^2$
${}^3_1\text{H}$ , ${}^7_4\text{Be}$ , ${}^{14}_6\text{C}$	100
${}^{18}_9\text{F}$ , ${}^{24}_{11}\text{Na}$ , ${}^{38}_{17}\text{Cl}$	1
${}^{54}_{25}\text{Mn}$ , ${}^{60}_{27}\text{Co}$ , ${}^{90}_{38}\text{Sr}$	1
${}^{64}_{29}\text{Cu}$ , ${}^{76}_{33}\text{As}$ , ${}^{75}_{34}\text{Se}$	10
${}^{99m}_{43}\text{Tc}$ , ${}^{105}_{45}\text{Rh}$ , ${}^{106}_{44}\text{Ru}$	10
${}^{111}_{47}\text{Ag}$ , ${}^{109}_{48}\text{Cd}$ , ${}^{99}_{43}\text{Tc}$	100
${}^{125}_{53}\text{I}$ , ${}^{131}_{53}\text{I}$ , ${}^{129}_{55}\text{Cs}$	10
${}^{134}_{55}\text{Cs}$ , ${}^{137}_{55}\text{Cs}$ , ${}^{140}_{56}\text{Ba}$	1
${}^{152}_{63}\text{Eu}$ , ${}^{154}_{63}\text{Eu}$ , ${}^{190}_{77}\text{Ir}$	1
${}^{204}_{81}\text{Tl}$ , ${}^{197}_{78}\text{Pt}$ , ${}^{210}_{83}\text{Bi}$	100
${}^{226}_{88}\text{Ra}$ , ${}^{227}_{89}\text{Ac}$ , ${}^{233}_{92}\text{U}$	1
${}^{239}_{94}\text{Pu}$ , ${}^{240}_{94}\text{Pu}$ , ${}^{252}_{98}\text{Cf}$	0.1
${}^{248}_{96}\text{Cm}$	0.01
$\beta$ emitter or EC emitter <sup>1</sup> with $E_e^{\max} < 0.2 \text{ MeV}$	100
$\beta$ or $\gamma$ emitter in general	1
$\alpha$ emitter or radioisotopes from spontaneous fission	0.1

In case of surface contaminations by different isotopes the following condition must be fulfilled:

$$\sum_{i=1}^N \frac{A_i}{A_i^{\max}} \leq 1 ,$$

where  $A_i$  are the observed surface contaminations and  $A_i^{\max}$  the corresponding limits as given in the table.



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<sup>1</sup> EC = electron capture

## E Definition of Radiation Areas

The definition of radiation areas varies somewhat in different countries, see Chap. 6 on ‘International Safety Standards for Radiation Protection’. In the following table the radiation areas according to the ICRP recommendations, adopted by many countries, are given.

<b>controlled area</b>	<b>surveyed area</b>	
exclusion area $> 3 \text{ mSv/h}$	6–20 mSv/yr	1–6 mSv/yr
	radiation-exposed workers (2000 h/yr)	
	cat. A	6–20 mSv/yr
	cat. B	1–6 mSv/yr
<b>neighborhood outside radiation areas</b>		
$< 1 \text{ mSv/yr}$	permanent residence	
<b>limit for the general public for discharges from nuclear facilities<sup>1</sup></b> $\leq 0.3 \text{ mSv/yr}$		

<sup>1</sup> This limit relates to maximum permitted releases of activity concentrations from radiation facilities (nuclear power plants, recycling facilities) via air and water, which are limited to 0.3 mSv/yr for the general public.

## F Radiation Weighting Factors $w_R$

The following radiation weighting factors  $w_R$  are almost generally accepted in all countries, see also Chap. 6.<sup>1</sup> In the early days of radiation protection the biological effect of radiation was taken care of by the so-called quality factors  $q$  (see also Chap. 2).

<b>type of radiation and energy range</b>	<b>radiation weighting factor <math>w_R</math></b>
photons, all energies	1
electrons and muons, all energies	1
neutrons	
$< 10 \text{ keV}$	5
$10 \text{ keV}–100 \text{ keV}$	10
$> 100 \text{ keV}–2 \text{ MeV}$	20
$> 2 \text{ MeV}–20 \text{ MeV}$	10
$> 20 \text{ MeV}$	5
protons, except recoil protons, energy $> 2 \text{ MeV}$	5
$\alpha$ particles, fission fragments, heavy nuclei	20

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<sup>1</sup> The radiation weighting factors as adopted in the United States, which are somewhat different, are given in Table 6.1 on page 94.

## G Tissue Weighting Factors $w_T$

The following tissue weighting factors  $w_T$  are almost generally accepted in all countries, see also Chaps. 2 and 6.<sup>1</sup>

organs or tissue	tissue weighting factor $w_T$
gonads	0.20
red bone marrow	0.12
large intestine	0.12
lung	0.12
stomach	0.12
bladder	0.05
chest	0.05
liver	0.05
esophagus	0.05
thyroid gland	0.05
skin	0.01
periosteum (bone surface)	0.01
other organs or tissue	0.05

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<sup>1</sup> The tissue weighting factors as adopted in the United States, which are somewhat different, are given in Table 6.2 on page 94.

## H Physical Constants

Constants, which are exact, are given with their precise values, if possible. They are characterized with an \*. For experimental values only the significant decimals are given, i.e., the measurement error is less than the last decimal place.

quantity	symbol	value	unit
velocity of light*	$c$	299 792 458	m/s
Planck constant	$h$	$6.626\,07 \times 10^{-34}$	J s
electron charge magnitude	$e$	$1.602\,177 \times 10^{-19}$	C
electron mass	$m_e$	$9.109\,38 \times 10^{-31}$	kg
proton mass	$m_p$	$1.672\,62 \times 10^{-27}$	kg
$\alpha$ -particle mass	$m_\alpha$	$6.644\,661\,8 \times 10^{-27}$	kg
unified atomic mass unit	$m_u$	$1.660\,54 \times 10^{-27}$	kg
electron–proton mass ratio	$m_e/m_p$	$5.446\,170\,21 \times 10^{-4}$	
permittivity of free space*	$\epsilon_0 = 1/(\mu_0 c^2)$	$8.854\,187\,\dots \times 10^{-12}$	F/m
permeability of free space*	$\mu_0$	$4\pi \times 10^{-7}$	N/A <sup>2</sup>
fine-structure constant	$\alpha = e^2/(4\pi \epsilon_0 \hbar c)$	$1/137.035\,999$	
classical electron radius	$r_e = e^2/(4\pi \epsilon_0 m_e c^2)$	$2.817\,940 \times 10^{-15}$	m
Compton wavelength	$\lambda_C = h/(m_e c)$	$2.426\,310\,2 \cdot 10^{-12}$	m
gravitational constant	$\gamma$	$6.674 \times 10^{-11}$	$\text{m}^3/(\text{kg s}^2)$
standard gravitational acceleration*	$g$	9.806 65	$\text{m/s}^2$
Avogadro constant	$N_A$	$6.022\,14 \times 10^{23}$	$\text{mol}^{-1}$
Boltzmann constant	$k$	$1.380\,65 \times 10^{-23}$	J/K
molar gas constant	$R (= N_A k)$	8.3144	$\text{J}/(\text{K mol})$
molar volume <sup>1</sup>	$V_{\text{mole}}$	$22.414 \times 10^{-3}$	$\text{m}^3/\text{mol}$
Rydberg energy	$E_{\text{Ry}} = m_e c^2 \alpha^2 / 2$	13.6057	eV
Stefan–Boltzmann constant	$\sigma = \pi^2 k^4 / (60 \hbar^3 c^2)$	$5.6704 \times 10^{-8}$	$\text{W m}^{-2} \text{ K}^{-4}$
Bohr radius	$a_0 = 4\pi \epsilon_0 \hbar^2 / (m_e c^2)$	$0.529\,177\,21 \times 10^{-10}$	m
Faraday constant	$F = e N_A$	96 485.309	C/mol
electron charge-to-mass ratio	$e/m_e$	$1.758\,820 \times 10^{11}$	C/kg

<sup>1</sup> at standard temperature and pressure ( $T = 273.15$  K,  $p = 101\,325$  Pa)

# I Useful Conversions

quantity	conversion
force	$1\text{ N} = 1\text{ kg m/s}^2$
work, energy	$1\text{ eV} = 1.602\,177 \times 10^{-19}\text{ J}$
	$1\text{ cal} = 4.186\text{ J}$
	$1\text{ erg} = 10^{-7}\text{ J}$
	$1\text{ kWh} = 3.6 \times 10^6\text{ J}$
energy dose	$1\text{ Gy} = 100\text{ rad}$
	$1\text{ rad} = 10\text{ mGy}$
dose equivalent	$1\text{ Sv} = 100\text{ rem}$
	$1\text{ rem} = 10\text{ mSv}$
ion dose	$1\text{ R} = 258\,\mu\text{C/kg}$ $\cong 8.77 \times 10^{-3}\text{ Gy (in air)}$
ion-dose rate	$1\text{ R/h} = 7.17 \times 10^{-8}\text{ A/kg}$
activity	$1\text{ Ci} = 3.7 \times 10^{10}\text{ Bq}$
	$1\text{ Bq} = 27.03\text{ pCi}$
pressure	$1\text{ bar} = 10^5\text{ Pa}$
	$1\text{ atm} = 1.013\,25 \times 10^5\text{ Pa}$
	$1\text{ Torr} = 1\text{ mm Hg}$ $= 1.333\,224 \times 10^2\text{ Pa}$
	$1\text{ kp/m}^2 = 9.806\,65\text{ Pa}$
charge	$1\text{ C} = 2.997\,924\,58 \times 10^9\text{ esu}^1$
length	$1\text{ m} = 10^{10}\text{ \AA}$
temperature	$\theta\text{ [}^\circ\text{C}] = T\text{ [K]} - 273.15$
	$T\text{ [}^\circ\text{Fahrenheit}] = 1.80\theta\text{ [}^\circ\text{C]} + 32$
	$= 1.80T\text{ [K]} - 459.67$
time	$1\text{ d} = 86\,400\text{ s}$
	$1\text{ yr} = 3.1536 \times 10^7\text{ s}$

<sup>1</sup> esu – electrostatic unit

## J List of Abbreviations

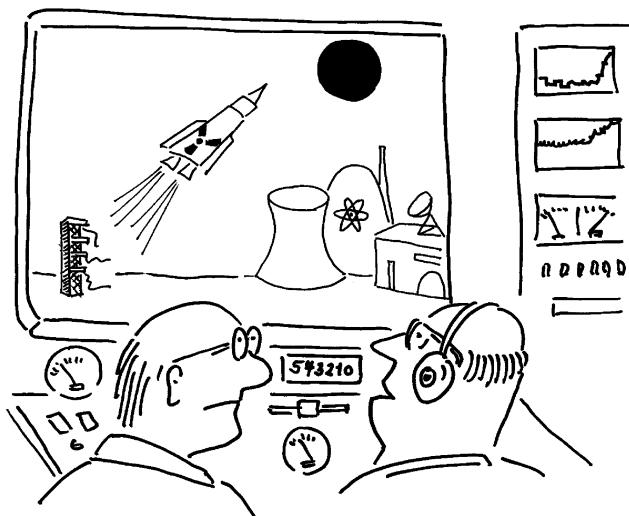
Å	– angstrom (unit of length); $1 \text{ \AA} = 10^{-10} \text{ m}$
a	– year (from the Latin word ‘annus’)
A	– ampere
ACS	– American Chemical Society
ADR	– Accord européen relatif au transport international des marchandises dangereuses par la route (European agreement about the transport of dangerous goods via roads)
AERB	– Atomic Energy Regulatory Board of India
AIDS	– Acquired Immune Deficiency Syndrome
ALARA	– as low as reasonably achievable
arctan	– arc tangent (Latin: <i>arcus tangens</i> ): inverse function of tangent (on pocket calculators usually denoted by $\tan^{-1}$ )
ALI	– Annual Limit on Intake
ANSTO	– Australian Nuclear Science and Technology Organisation
ARPANS	– Australian Radiation Protection and Nuclear Safety
atm	– atmosphere (unit of pressure)
bar	– unit of pressure, from the Greek $\beta\alpha\rho\omega\varsigma$ , ‘weight’
barn	– unit of the (total) cross section ( $= 10^{-24} \text{ cm}^2$ )
BF <sub>3</sub>	– boron trifluoride
BMU	– federal ministry for environment in Germany (Bundesministerium für Umwelt)
Bq	– becquerel
C	– coulomb (unit of the electric charge)
cal	– calory (unit of energy)
CASTOR	– cask for storage and transport of radioactive material
CEDE	– Committed Effective Dose Equivalent
CERN	– Conseil Européen pour la Recherche Nucléaire (European Center for Particle Physics in Geneva)
Ci	– curie
CW lasers	– Continuous-Wave lasers
d	– day (from the Latin word ‘dies’)
DARI	– Dose Annuelle due aux Radiations Internes (annual dose due to internal radiation from the body)
DF	– decontamination factor
DIN	– German institute for engineering standards (Deutsches Institut für Normung)
DIS dosimeter	– Direct Ion Storage dosimeter

DNA	– deoxyribonucleic acid
DTPA	– diethylenetriamine pentaacetate
e	– Eulerian number ( $e = 2.718\,281\dots$ )
EC	– electron capture (mostly from the K shell)
EDTA	– ethylenediamine tetraacetate
erg	– unit of energy ( $1\text{ g cm}^2/\text{s}^2$ ); from the Greek $\epsilon\rho\gamma\omega\nu$ , ‘work’
ERR	– Excess Relative Risk
esu	– unit of charge: electrostatic unit
EU	– European Union
EURATOM	– European Atomic Union
exp	– short for the exponential function
eV	– electron volt
F	– farad (unit of capacitance)
FAO	– Food and Agricultural Organization of the United Nations
FWHM	– Full Width at Half Maximum
GBq	– gigabecquerel
GeV	– giga electron volt
GGVS	– German ordinance for the transport of dangerous goods (Gefahrgut Verordnung Straße)
GM counter	– Geiger–Müller counter
GSF	– German research center for environment and health (Forschungszentrum für Umwelt und Gesundheit)
GSI	– Gesellschaft für Schwerionenforschung, Darmstadt, Germany
Gy	– gray
h	– hour (from the Latin word ‘hora’)
hPa	– hectopascal
HPGe detector	– High Purity Germanium detector
HTR	– high-temperature reactor
Hz	– hertz (1/s)
IAD	– inevitable annual dose
IAEA	– International Atomic Energy Agency
IAEO	– International Atomic Energy Organization
ICAO	– International Civil Aviation Organization (Technical Instructions for Safe Transport of Dangerous Goods by Air)
ICNIRP	– International Commission on Non-Ionizing Radiation Protection
ICRP	– International Commission on Radiological Protection
ICRU	– International Commission on Radiation Units and Measurements
ILO	– International Labor Organization
IMDG	– International Maritime Dangerous Goods code

ITER	– International Thermonuclear Experimental Reactor
IUPAC	– International Union for Pure and Applied Chemistry
IUPAP	– International Union for Pure and Applied Physics
J	– joule (unit of energy; $1\text{ J} = 10^7\text{ erg}$ )
JAZ	– annual intake (from the German ‘Jahresaktivitätszufuhr’)
JET	– Joint European Torus
K	– kelvin (absolute temperature)
kBq	– kilobecquerel
kerma	– kinetic energy released per unit mass (also: kinetic energy released in matter (or material))
keV	– kilo electron volt
kHz	– kilohertz (or kilocycle)
kJ	– kilojoule
kp	– kilopond
kT	– kiloton (explosive)
kV	– kilovolt
LASER	– Light Amplification by Stimulated Emission of Radiation
LD	– lethal dose
LEP	– Large Electron–Positron collider at CERN
LET	– Linear Energy Transfer
LINAC	– linear accelerator
ln	– logarithmus naturalis (natural logarithm)
LNT	– Linear No-Threshold hypothesis
mA	– milliampere
MBq	– megabecquerel
$\mu\text{C}$	– microcoulomb
mCi	– millicurie
$\mu\text{Ci}$	– microcurie
meV	– milli electron volt
MeV	– mega electron volt
mGy	– milligray
$\mu\text{Gy}$	– microgray
mK	– millikelvin
$\mu\text{K}$	– microkelvin
mole	– amount of material which contains $6.022 \times 10^{23}$ molecules/atoms (= Avogadro number)
MOSFET	– Metal Oxide Field Effect Transistor
MOX	– Mixture of Oxides

mrem	– millirem
MRT	– Microbeam Radiation Therapy
mSv	– millisievert
$\mu$ Sv	– microsievert
mV	– millivolt
MW	– megawatt
N	– newton (unit of force)
NASA	– National Aeronautics and Space Administration
NEA	– Nuclear Energy Agency
NIR	– Non-Ionizing Radiation
NPL	– National Physical Laboratory
nSv	– nanosievert
OECD	– Organization for Economic Cooperation and Development
$\Omega$	– ohm
Pa	– pascal (unit of pressure)
PBD	– 2-(4-tert.-butylene-phenyl)- 5-(4-biphenyl-1,3,4-oxadiazole)
pCi	– picocurie
PET	– Positron-Emission Tomography
pF	– picofarad ( $10^{-12}$ F)
PIPS detector	– Passive Implanted Planar Silicon detector
PM	– photomultiplier
PMMA	– polymethyl methacrylate
ppm	– parts per million ( $10^{-6}$ )
PTB	– German national physical laboratory for weights and measures (Physikalisch–Technische Bundesanstalt in Braunschweig, equivalent to the British NPL)
R	– roentgen
rad	– radiation absorbed dose
rad	– radian (unit of angle, the full radian is $2\pi$ )
Radar	– Radio Detecting and Ranging
rem	– roentgen equivalent man
RBE	– relative biological effectiveness
RID	– règlement international concernant le transport des marchandises dangereuses provision about the transport of dangerous goods
RNA	– ribonucleic acid
RTG	– Radioisotope Thermoelectric Generator
SAR	– specific absorption rate

steradian	– unit of solid angle; the full solid angle corresponds to the surface of the unit sphere: $4\pi$
StrlSchV	– Strahlenschutzverordnung (German radiation-protection ordinance)
Sv	– sievert
TeV	– tera electron volt
TLD	– thermoluminescence dosimeter
TNT	– trinitrotoluol (explosive)
Torr	– torricelli (unit of pressure, mm column of mercury)
UMTS	– Universal Mobile Telecommunications System
UN	– United Nations
UNSCEAR	– United Nations Scientific Committee on the Effects of Atomic Radiation
UV	– ultraviolet
UVA	– ultraviolet type A radiation, wavelength 400–315 nm
UVB	– ultraviolet type B radiation, wavelength 315–280 nm
UVC	– ultraviolet type C radiation, wavelength 280–100 nm
V	– volt
VDI	– Verein Deutscher Ingenieure (association of German engineers)
WHO	– World Health Organization
W	– watt (unit of power),
W s	watt second (unit of energy)



"The perfect final deposit: A Black Hole!"

© by Claus Grupen

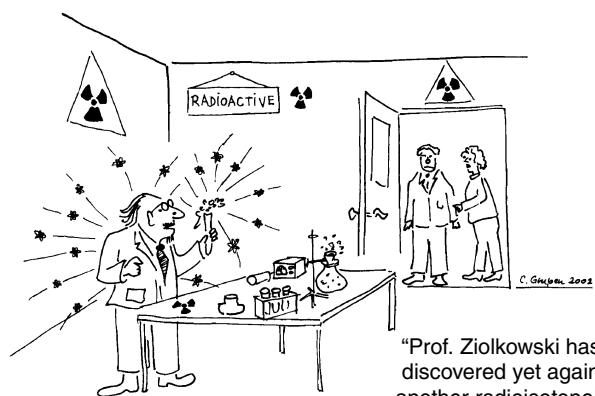
## K List of Elements\*

- 1 H hydrogen (Greek: *νδωρ*, hydor, water + *γεινομαι*, geinomai, to engender; Latin: hydrogenium);  
 D =  $^2_1\text{H}$  deuterium (Greek: *δευτερος*, deuteros, second) and T =  $^3_1\text{H}$  tritium (Greek: *τριτος* tritos, third) are isotopes of hydrogen
- 2 He helium (Greek: *ηλιος*, helios, sun)
- 3 Li lithium (Greek: *λιθος*, lithos, stone, rock)
- 4 Be beryllium (Greek: *βηρυλλος*, beryllos, beryl)
- 5 B boron (Latin: boracium; Arabic: borax)
- 6 C carbon (Latin: carbo, coal; French: charbon, charcoal)
- 7 N nitrogen (Greek: *νιτρον*, nitron + *γεινομαι*, geinomai, to engender, soda forming; Latin: nitrogenium)
- 8 O oxygen (Greek: *οξυς*, oxys, acid + *γεινομαι*, geinomai, to engender, acid forming; Latin: oxygenium)
- 9 F fluorine (Latin: fluere, to flow, to stream)
- 10 Ne neon (Greek: *νεος*, neos, new, young)
- 11 Na sodium (Latin: sodanum; Hebrew: neter, soda; German: Natrium; from the Arabic word ‘natrun’ = soda)
- 12 Mg magnesium (Greek: *Μαγνησια*, Magnesia (district in the Greek town Thessaly))
- 13 Al aluminum (Latin: alumen, a bitter salt)
- 14 Si silicon (Latin: silex, flint)
- 15 P phosphorus (Greek: *φωσφορος*, phosphoros, light bearing, luminous)
- 16 S sulphur (Latin: sulfur)
- 17 Cl chlorine (Greek: *χλωρος*, chloros, light green, green-yellow)
- 18 Ar argon (Greek: *αργον*, argon, inactive, idle)
- 19 K potassium (German: Kalium from the Arabic word al-qali = ash or English: potash)
- 20 Ca calcium (Latin: calx, limestone)
- 21 Sc scandium (Latin: from Scandinavia)
- 22 Ti titanium (Greek: *τιτανος*, Titans, children of the Earth)
- 23 V vanadium (Vanadis, Scandinavian goddess of beauty)
- 24 Cr chromium, (Greek: *χρωμα*, chroma, color)
- 25 Mn manganese, (Greek: *Μαγνησια*, Magnesia (district in the Greek town Thessaly); Latin: magnes, magnet)
- 26 Fe iron (Latin: ferrum)
- 27 Co cobalt (German: Kobold, goblin, evil spirit)
- 28 Ni nickel (German: Kupfernickel = devil’s copper)
- 29 Cu copper (Greek: *κυπριος*, kuprios; Latin: cuprum; metal from the island of Cyprus)
- 30 Zn zinc (German: Zink, sharp point)
- 31 Ga gallium (Latin: Gallia, France)
- 32 Ge germanium (Latin: Germania, Germany)
- 33 As arsenic (Arabic: al-zarnikh, gold-colored)
- 34 Se selenium (Greek: *σεληνη*, selene, moon)
- 35 Br bromine (Greek: *βρομος*, bromos, stench)
- 36 Kr krypton (Greek: *κρυπτος*, kryptos, hidden)
- 37 Rb rubidium (Latin: rubidus, deep red)
- 38 Sr strontium (Strontian, village in Scotland)
- 39 Y yttrium (after the Swedish village Ytterby)

\* see also [www.periodensystem.info/periodensystem.htm](http://www.periodensystem.info/periodensystem.htm)  
 resp. [www.webelements.com/](http://www.webelements.com/)  
 or <http://elements.vanderkrogt.net/elem/>

- 40 Zr zirconium (Persian: zargûn, gold color)
- 41 Nb niobium (*Nιοβη*, Niobe, daughter of Tantalus)
- 42 Mo molybdenum (Greek: *μολυβδος*, molybdos, lead ore)
- 43 Tc technetium (Greek: *τεχνητος*, technetos, artificial)
- 44 Ru ruthenium (Latin: Ruthenia = Ukraine, sometimes Russia is meant)
- 45 Rh rhodium (Greek: *ροδον*, rodon, rose)
- 46 Pd palladium (Greek: named after Pallas Athene, the Greek goddess of wisdom)  
*Παλλασ Αθηνη*
- 47 Ag silver (Latin: argentum)
- 48 Cd cadmium (named after ‘Kadmos’, the founder of the Egyptian city of Thebes).
- 49 In indium (named after the indigo blue spectral color)
- 50 Sn tin (Latin: stannum or Indo-European: stag, dripping)
- 51 Sb antimonium (Latin: stibium or Greek: *στιβι*, stibi, cosmetic powder)
- 52 Te tellurium (Latin: tellus, earth, ground)
- 53 I iodine (Greek: *ιοειδης*, ioeides, violet color)
- 54 Xe xenon (Greek: *ξενος*, xenos, strange)
- 55 Cs cesium (Latin: caesius = bluish gray)
- 56 Ba barium (Greek: *βαρυς*, barys, heavy)
- 57 La lanthanum (Greek: *λανθανω*, lanthanoo, to lie hidden)
- 58 Ce cerium (Ceres, asteroid discovered in 1801)
- 59 Pr praseodymium (Greek: *πρασινος* + *διδυμος*, prasios + didymos, green and twins)
- 60 Nd neodymium (Greek: *νεος* + *διδυμος*, neos + didymos, new and twins)
- 61 Pm promethium (Greek: *Προμηθευς*, named after Prometheus)
- 62 Sm samarium (samarskite, mineral named after V.E. Samarskij-Byhovec)
- 63 Eu europium (Latin: Europa, Europe)
- 64 Gd gadolinium (gadolinite, mineral named after Johan Gadolin)
- 65 Tb terbium (named after the Swedish village Ytterby)
- 66 Dy dysprosium (Greek: *δυσπροσιτος*, dysprositos, hard to obtain)
- 67 Ho holmium (Latin: Holmia = Stockholm)
- 68 Er erbium (named after the Swedish village Ytterby)
- 69 Tm thulium (Latin: Thule in Scandinavia)
- 70 Yb ytterbium (named after the Swedish village Ytterby)
- 71 Lu lutetium (after the Roman name of Paris: Lutetia Parisorum)
- 72 Hf hafnium (Latin: Hafnia = København, Copenhagen)
- 73 Ta tantalum (Greek: *Τανταλος*, Tantalos, figure in Greek mythology)
- 74 W tungsten (Swedish: Tung Sten, heavy stone; Wolfram: mineral wolframite, from ‘Wolf Rahm’ (German for wolf’s foam))
- 75 Re rhenium (Latin: Rhenus, Rhine)
- 76 Os osmium (Greek: *οσμη*, osme, stench)
- 77 Ir iridium (Greek: *Ιρις*, Greek goddess of the rainbow)
- 78 Pt platinum (Spanish: platina (del Pinto) = small silver (beads) of the river Pinto)
- 79 Au gold (Latin: aurum)
- 80 Hg mercury (Greek: *υδραργυρος*, hydraryros, liquid silver; Latin: hydrargyrum)
- 81 Tl thallium (Greek: *θαλλος*, thallos, green shot)
- 82 Pb lead (Latin: plumbum)
- 83 Bi bismuth (Latin: bisemutum; German: Weisse Masse, white substance)
- 84 Po polonium (Latin: Polonia = Polska, Poland)
- 85 At astatine (Greek: *αστατος*, astatos, unstable)
- 86 Rn radon (Latin: nitens, shining; named after the element radium, changed to radon to match the endings of most other noble gases)
- 87 Fr francium (Latin: named after France)
- 88 Ra radium (Latin: radius, ray)
- 89 Ac actinium (Greek: *ακτις*, aktis, ray)

- |  |   |
|--|---|
| 90 Th thorium (Thor, Scandinavian god of war)  | 103 Lr lawrencium (named after Ernest O. Lawrence)              |
| 91 Pa protactinium (Greek: $\pi\rho\omega\tau\sigma\varsigma$ + actinium, first element after actinium in the uranium–actinium decay series) | 104 Rf rutherfordium (named after Ernest Rutherford)            |
| 92 U uranium (named after the planet Uranus)   | 105 Db dubnium (named after Dubna, a town in the Moscow region) |
| 93 Np neptunium (named after the planet Neptune)   | 106 Sg seaborgium (named after Glenn T. Seaborg)                |
| 94 Pu plutonium (named after the dwarf planet Pluto ( $\Pi\lambda\omega\tau\omega\nu$ , Plouton), the Greek god of the underworld)           | 107 Bh bohrium (named after Niels Bohr)                         |
| 95 Am americium (Latin: America)   | 108 Hs hassium (named after the German state Hassia, Hessen)    |
| 96 Cm curium (named after Marie Curie)   | 109 Mt meitnerium (named after Lise Meitner)                    |
| 97 Bk berkelium (Berkeley, town in California)   | 110 Ds darmstadtium (named after Darmstadt, a town in Germany)  |
| 98 Cf californium (California, state of the USA)   | 111 Rg roentgenium (named after Wilhelm Conrad Röntgen)         |
| 99 Es einsteinium (named after Albert Einstein)  | 112 Cn copernicium (named after Nicolaus Copernicus)            |
| 100 Fm fermium (named after Enrico Fermi)  | 113 †   |
| 101 Md mendelevium (named after Dmitri I. Mendeleyev)  | 114 †   |
| 102 No nobelium (named after Alfred Nobel)   | 115 †   |
|  | 116 †   |
|  | 118 †   |



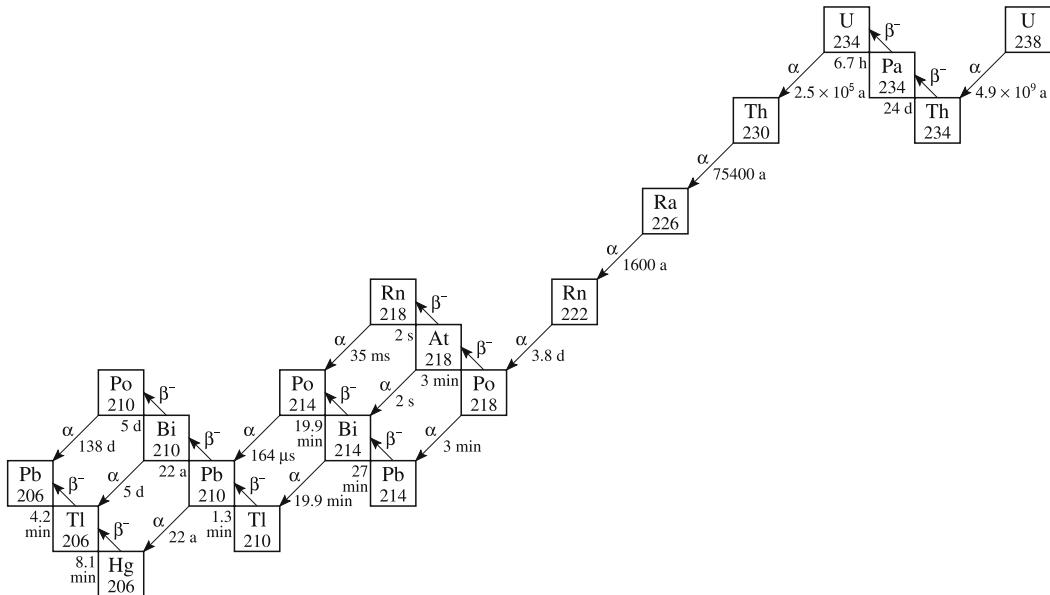
"Prof. Ziolkowski has discovered yet again another radioisotope!"

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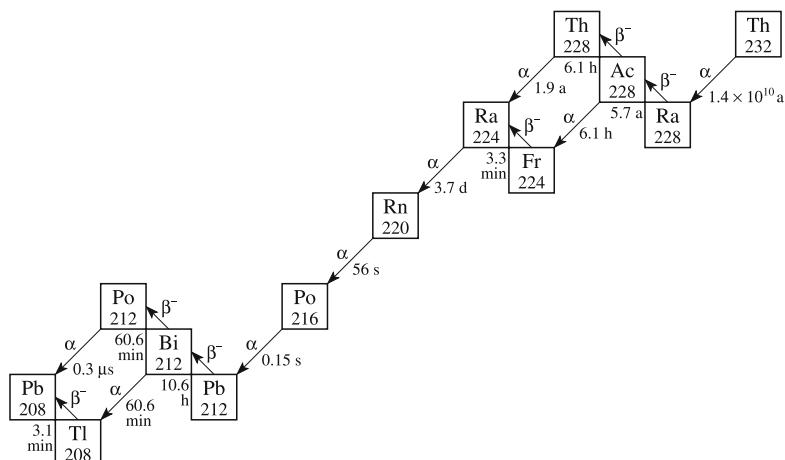
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<sup>†</sup>  $Z = 113, 114, 115, 116, 118$ : Lawrence Livermore–Dubna Collaboration, Russia, and Berkeley, USA

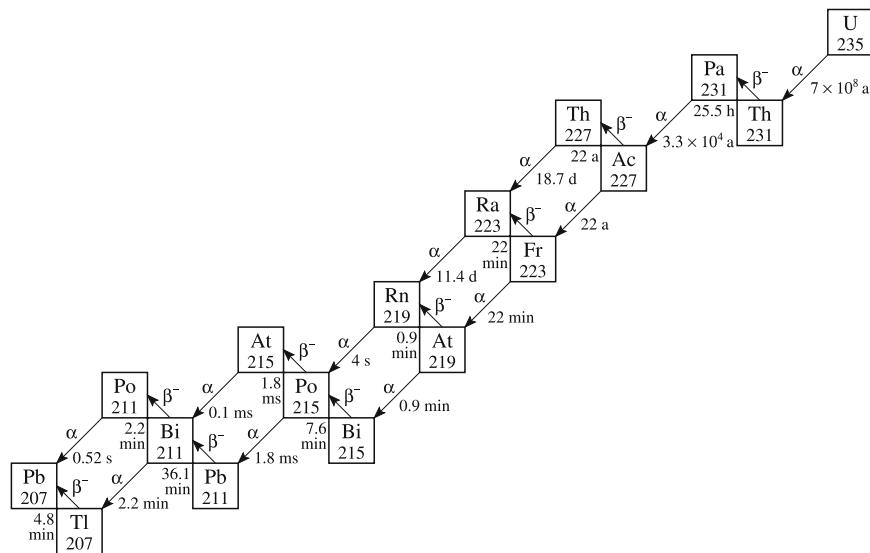
## L Decay Chains



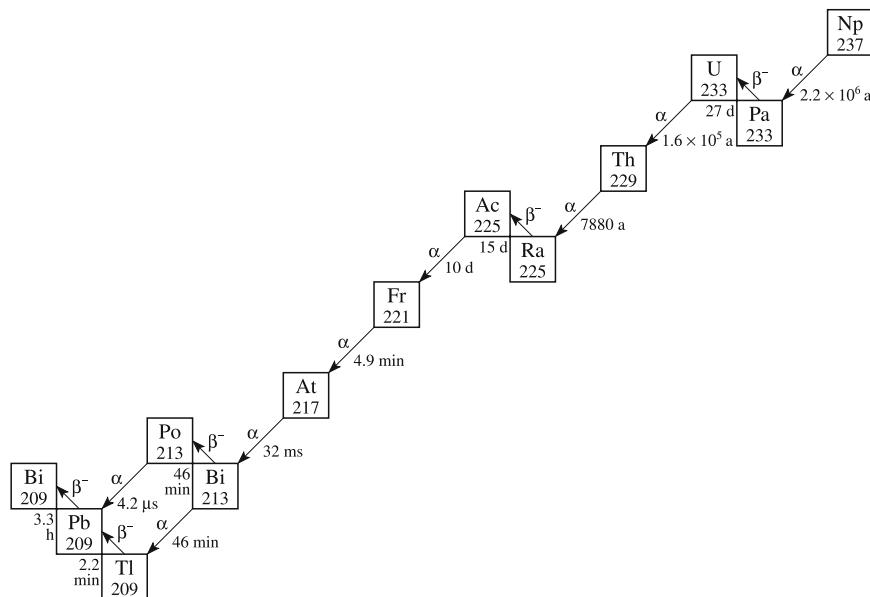
**Figure L.1**  
Uranium ( $^{238}\text{U}$ ) decay chain  
(a = annum, year)



**Figure L.2**  
Thorium ( $^{232}\text{Th}$ ) decay chain  
(a = annum, year)



**Figure L.3**  
Actinium ( $^{235}\text{U}$ ) decay chain  
(a = annum, year)



**Figure L.4**  
Neptunium ( $^{237}\text{Np}$ ) decay chain  
(a = annum, year)

## M List of Isotopes Frequently Used in Nuclear Medicine and Radiology

isotope	half-life	decay	main energy	application
protons	stable		$\approx 200$ MeV	particle therapy
$^3\text{H}$	12.3 yrs	$\beta^-$ , no $\gamma$	0.02 MeV	total body water content determination
$^{11}\text{B}$	stable			melanoma and brain tumor treatment
$^{11}\text{C}$	20.4 min	$\beta^+$ , no $\gamma$	1.0 MeV	Positron-Emission Tomography; PET scans
$^{12}\text{C}$	stable		$\approx 300$ MeV per nucleon	particle therapy
$^{14}\text{C}$	5730 yrs	$\beta^-$ , no $\gamma$	0.2 MeV	e.g. pancreatic studies
$^{13}\text{N}$	10 min	$\beta^+$ , no $\gamma$	1.2 MeV	Positron-Emission Tomography; PET scans
$^{15}\text{O}$	2 min	$\beta^+$ , no $\gamma$	1.7 MeV	Positron-Emission Tomography; PET scans
$^{18}\text{F}$	110 min	$\beta^+$ , no $\gamma$	0.6 MeV	Positron-Emission Tomography; PET scans
$^{22}\text{Na}$	2.6 yrs	$\beta^+$ $\gamma$	0.5 MeV ... 1275 keV	electrolyte studies
$^{24}\text{Na}$	15 h	$\beta^-$ $\gamma$	1.4 MeV ... 2754 keV ...	studies of electrolytes within the body
$^{32}\text{P}$	14.3 d	$\beta^-$ , no $\gamma$	1.7 MeV	treatment against excess of red blood cells
$^{42}\text{K}$	12.4 h	$\beta^-$ $\gamma$	3.5 MeV 1525 keV ...	for measurement of coronary blood flow
$^{47}\text{Ca}$	4.5 d	$\beta^-$ $\gamma$	0.7 MeV ... 1297 keV ...	bone metabolism
$^{51}\text{Cr}$	27.7 d	$\gamma$ EC	320 keV	labeling of red blood cells
$^{59}\text{Fe}$	44.5 d	$\beta^-$ $\gamma$	0.5 MeV ... 1099 keV ...	metabolism in the spleen
$^{57}\text{Co}$	272 d	$\gamma$ EC	122 keV ...	marker to estimate organ size

isotope	half-life	decay	main energy	application
$^{58}\text{Co}$	71 d	$\beta^+$ $\gamma$ EC	0.5 MeV ... 811 keV	gastrointestinal absorption
$^{60\text{m}}\text{Co}$	10.5 min	$\gamma$	59 keV	external beam radiotherapy
$^{60}\text{Co}$	5.3 yrs	$\beta^-$ $\gamma$ $\gamma$	0.3 MeV ... 1173 keV 1332 keV	tumor treatment
$^{62}\text{Cu}$	9.7 min	$\beta^+$ $\gamma$	2.9 MeV ... 1173 keV ...	positron-emitting radionuclide for PET
$^{64}\text{Cu}$	12.7 h	$\beta^-$ $\beta^+$ $\gamma$ EC	0.6 MeV 0.7 MeV 1346 keV	study of genetic of diseases
$^{67}\text{Cu}$	61.9 h	$\beta^-$ $\gamma$	0.4 MeV ... 185 keV ...	radioimmunotherapy
$^{64}\text{Ga}$	2.6 min	$\beta^+$ $\gamma$	2.9 MeV ... 992 keV ...	treatment of pulmonary diseases
$^{67}\text{Ga}$	78.3 h	$\gamma$ EC, no $\beta^+$	93 keV ...	tumor imaging
$^{68}\text{Ga}$	67.6 min	$\beta^+$ $\gamma$	1.9 MeV ... 1077 keV ...	study thrombosis and atherosclerosis detection of pancreatic cancer
$^{68}\text{Ge}$	271 d	no $\beta^+$ , no $\gamma$ , EC		PET imaging
$^{72}\text{As}$	26 h	$\beta^+$ $\gamma$	2.5 MeV ... 834 keV ...	planar imaging, SPECT, or PET
$^{75}\text{Se}$	120 d	$\gamma$ EC	265 keV ...	radiotracer used in brain studies scintigraphy scanning study of the production of digestive enzymes
$^{81\text{m}}\text{Kr}$ from $^{81}\text{Rb}$	13 s	$\gamma$ EC	190 keV	pulmonary ventilation
$^{82}\text{Rb}$ from $^{82}\text{Sr}$	6.3 h	$\beta^+$ $\gamma$	0.8 MeV ... 776 keV ...	PET agent in myocardial perfusion imaging
$^{89}\text{Sr}$	50.5 d	$\beta^-$ $\gamma$	1.5 MeV ... 909 keV	reducing the pain due to prostate and bone cancer
$^{90}\text{Y}$	64.1 h	$\beta^-$ $\gamma$	2.3 MeV ... 2186 keV ...	cancer brachytherapy

isotope	half-life	decay	main energy	application
<sup>99</sup> Mo	66 h	$\beta^-$ $\gamma$	1.2 MeV ... 740 keV ...	parent of <sup>99m</sup> Tc
<sup>99m</sup> Tc	6 h	$\gamma$	141 keV ...	skeleton, heart muscle, brain, thyroid, lungs, liver, spleen, kidney, gall bladder, bone marrow, salivary, and lacrimal glands
<sup>103</sup> Ru	39.4 d	$\beta^-$ $\gamma$	0.2 MeV ... 497 keV ...	myocardial blood flow
<sup>103</sup> Pd	17 d	$\gamma$ EC	357 keV ...	brachytherapy for early prostate cancer
<sup>109</sup> Cd	463 d	no $\gamma$ , EC		cancer detection, pediatric imaging
<sup>111</sup> In	2.8 d	$\gamma$ EC, no $\beta^+$	245 keV ...	brain studies
<sup>117m</sup> Sn	13.6 d	$\gamma$	159 keV ...	bone cancer pain relief
<sup>122</sup> I	3.6 min	$\beta^+$ $\gamma$	3.1 MeV ... 564 keV ...	brain blood flow studies
<sup>123</sup> I	13.2 h	$\gamma$ EC, no $\beta^+$	159 keV ...	diagnosis of the thyroid function
<sup>125</sup> I	59.4 d	$\gamma$ EC	35 keV	cancer brachytherapy (prostate and brain) filtration rate of kidneys
<sup>131</sup> I	8.0 d	$\beta^-$ $\gamma$	0.6 MeV ... 364 keV ...	treatment of thyroid cancer with beta therapy
<sup>132</sup> I	2.3 h	$\beta^-$ $\gamma$	2.1 MeV ... 668 keV ...	marking of red blood cells
<sup>130</sup> Cs	29.2 min	$\beta^+$ $\beta^-$ $\gamma$ EC	2.0 MeV ... 0.4 MeV 536 keV	myocardial localizing agent
<sup>127</sup> Xe	36.4 d	$\gamma$ EC	203 keV ...	neuroimaging for brain disorders
<sup>133</sup> Xe	5.3 d	$\beta^-$ $\gamma$	0.3 MeV ... 81 keV ...	lung ventilation studies
<sup>137</sup> Cs	30.2 yrs	$\beta^-$ $\gamma$	0.5 MeV ... 662 keV ...	brachytherapy
<sup>141</sup> Ce	32.5 d	$\beta^-$ $\gamma$	0.4 MeV ... 145 keV	gastrointestinal tract diagnosis

isotope	half-life	decay	main energy	application
<sup>153</sup> Sm	46.3 h	$\beta^-$	0.7 MeV ...	prostate and breast cancer relieving pain of secondary cancers
		$\gamma$	103 keV ...	
<sup>155</sup> Eu	4.8 yrs	$\beta^-$	0.17 MeV ...	osteoporosis detection
		$\gamma$	87 keV ...	
<sup>165</sup> Dy	2.4 h	$\beta^-$	1.3 MeV ...	treatment of arthritis
		$\gamma$	95 keV ...	
<sup>166</sup> Ho	26.8 h	$\beta^-$	1.9 MeV ...	treatment of liver tumors
		$\gamma$	81 keV ...	
<sup>169</sup> Er	9.4 d	$\beta^-$	0.3 MeV ...	for relieving arthritis
		$\gamma$	110 keV ...	
<sup>170</sup> Tm	129 d	$\beta^-$	1.0 MeV ...	portable blood irradiations for leukemia
		$\gamma$	84 keV ...	
<sup>169</sup> Yb	32 d	$\gamma$ EC	63 keV ...	cerebrospinal fluid studies in the brain
<sup>177</sup> Lu	6.7 d	$\beta^-$	0.5 MeV ...	$\beta$ radiation for small tumors $\gamma$ rays for imaging
		$\gamma$	208 keV ...	
<sup>178</sup> Ta	9.3 min	$\beta^+$	0.9 MeV	viewing of heart and blood vessels
		$\gamma$	93 keV ...	
<sup>182</sup> Ta	115 d	$\beta^-$	0.5 MeV ...	bladder cancer treatment
		$\gamma$	68 keV ...	
<sup>186</sup> Re	3.7 d	$\beta^-$	1.1 MeV ...	for pain relief in bone cancer for imaging
		$\gamma$	137 keV ...	
<sup>188</sup> Re	17 h	$\beta^-$	2.1 MeV ...	$\beta$ irradiation of coronary arteries
		$\gamma$	155 keV ...	
<sup>191m</sup> Ir	5 s	$\gamma$	129 keV ...	cardiovascular angiography
<sup>192</sup> Ir	74 d	$\beta^-$	0.7 MeV ...	cancer brachytherapy source supplied in wire form
		$\gamma$	317 keV ...	
<sup>198</sup> Au	2.7 d	$\beta^-$	1.0 MeV ...	brachytherapy and liver treatment
		$\gamma$	412 keV ...	
<sup>201</sup> Tl	73.1 h	$\gamma$ EC	167 keV ...	diagnosis of coronary artery disease
<sup>213</sup> Bi	45.6 min	$\alpha$	5.87 MeV ...	Targeted Alpha Therapy (TAT)
		$\beta^-$	1.4 MeV ...	
		$\gamma$	440 keV ...	

<b>isotope</b>	<b>half-life</b>	<b>decay</b>	<b>main energy</b>	<b>application</b>
$^{226}\text{Ra}$	1600 yrs	$\alpha$	4.78 MeV ...	brachytherapy
		$\gamma$	186 keV ...	
$^{238}\text{Pu}$	87.7 yrs	$\alpha$	5.50 MeV ...	pacemaker (no $^{236}\text{Pu}$ contaminants)
		$\gamma$	43 keV ...	
		sf		
$^{241}\text{Am}$	432 yrs	$\alpha$	5.49 MeV ...	osteoporosis detection, heart imaging
		$\gamma$	60 keV ...	
		sf		
$^{252}\text{Cf}$	2.6 yrs	$\alpha$	6.12 MeV ...	brain cancer treatment
		$\gamma$	43 keV ...	
		sf		

## Abbreviations

PET – Positron-Emission Tomography

SPECT – Single Photon Emission Computed Tomography

TAT – Targeted Alpha Therapy

EC – electron capture

sf – spontaneous fission

all  $\gamma$  energies are given in keV

for  $\beta$  decays the endpoint energies (i.e. the maximum energies) are given

for  $\alpha$  decays the discrete energies are given

## References:

Radioisotopes in Medicine: [www.world-nuclear.org/info/inf55.htm](http://www.world-nuclear.org/info/inf55.htm),  
[www.expresspharmaonline.com/20050331/radiopharmaceuticals01.shtml](http://www.expresspharmaonline.com/20050331/radiopharmaceuticals01.shtml),  
[www.radiochemistry.org/nuclearmedicine/frames/medical\\_radioisotopes/index.html](http://www.radiochemistry.org/nuclearmedicine/frames/medical_radioisotopes/index.html)

## N Critical Organs for Various Radioisotopes

isotope	physical half-life	effective half-life	emitter	critical organ
<sup>3</sup> H	12.3 yrs	10 d	$\beta^-$	whole body
<sup>7</sup> Be	53.3 d	53.3 d	$\gamma$ , EC	whole body, bones
<sup>10</sup> Be	$1.6 \times 10^6$ yrs	4 yrs	$\beta^-$	whole body
<sup>14</sup> C	5730 yrs	40 d	$\beta^-$	whole body
<sup>16</sup> N	7.1 s	7.1 s	$\beta^-, \gamma$	lung
<sup>18</sup> F	110 min	110 min	$\beta^+$	skeleton
<sup>22</sup> Na	2.6 yrs	11 d	$\beta^+, \gamma$	whole body
<sup>24</sup> Na	15 h	14 h	$\beta^-, \gamma$	gastrointestinal tract
<sup>32</sup> Si	172 yrs	100 d	$\beta^-$	whole body
<sup>32</sup> P	14.3 d	14.1 d	$\beta^-$	bones
<sup>33</sup> P	25.3 d	25.3 d	$\beta^-$	bones
<sup>35</sup> S	87.5 d	44 d	$\beta^-$	whole body
<sup>36</sup> Cl	$3 \times 10^5$ yrs	30 d	$\beta^-$	whole body
<sup>39</sup> Ar	269 yrs	5 min	$\beta^-$	lung
<sup>40</sup> K	$1.28 \times 10^9$ yrs	30 d	$\beta^+, \beta^-, \gamma$	whole body
<sup>45</sup> Ca	163 d	163 d	$\beta^-, \gamma$	bones
<sup>47</sup> Ca	4.5 d	4.5 d	$\beta^-, \gamma$	bones
<sup>51</sup> Cr	27.7 d	22.8 d	$\gamma$ , EC	lung, gastrointestinal tract
<sup>54</sup> Mn	312 d	88.5 d 23 d	$\gamma$ , EC	lung liver
<sup>55</sup> Fe	2.7 yrs	1.1 yrs	EC	spleen
<sup>59</sup> Fe	44.5 d	41.9 d	$\beta^-, \gamma$	spleen
<sup>60</sup> Co	5.3 yrs	117 d	$\beta^-, \gamma$	lung

<b>isotope</b>	<b>physical half-life</b>	<b>effective half-life</b>	<b>emitter</b>	<b>critical organ</b>
<sup>63</sup> Ni	100 yrs	variable	$\beta^-$	whole body
<sup>64</sup> Cu	12.7 h	12 h	$\beta^+, \beta^-, \gamma$ , EC	whole body
<sup>65</sup> Zn	245 d	194 d 81 d	$\beta^+, \gamma$ , EC	whole body lung
<sup>75</sup> Se	120 d	61 d 10 d	$\gamma$ , EC	lung kidney
<sup>82</sup> Br	35.3 h	30.5 h	$\beta^-, \gamma$	whole body
<sup>81m</sup> Kr	13.1 s	13 s	$\gamma$ , EC	lung
<sup>85</sup> Kr	10.7 yrs	5 min	$\beta^-, \gamma$	whole body
<sup>86</sup> Rb	18.7 d	13 d	$\beta^-, \gamma$ , EC	whole body, pancreas, liver
<sup>87</sup> Rb	$4.8 \times 10^{10}$ yrs	44 d	$\beta^-, \gamma$ , EC	whole body, pancreas, liver
<sup>85</sup> Sr	65 d	65 d	$\gamma$ , EC	bones
<sup>89</sup> Sr	50.5 d	50.5 d	$\beta^-, \gamma$	bones
<sup>90</sup> Sr	28.6 yrs	18 yrs	$\beta^-$	bones
<sup>90</sup> Y	64.1 h	30 h	$\beta^-, \gamma$	gastrointestinal tract
<sup>91</sup> Y	58.5 d	58 h	$\beta^-, \gamma$	bones, liver
<sup>95</sup> Zr	64.0 d	64 d	$\beta^-, \gamma$	bones
<sup>99</sup> Mo	66.0 h	65 h	$\beta^-, \gamma$	bones, liver
<sup>99m</sup> Tc	6 h	4 h	$\gamma$	thyroid, gastrointestinal tract
<sup>103</sup> Ru	39.4 d	35 d	$\beta^-, \gamma$	lung, whole body
<sup>105</sup> Ru	4.4 d	4 d	$\beta^-, \gamma$	lung, whole body
<sup>106</sup> Ru	373.6 d	35 d	$\beta^-$	lung, whole body
<sup>110m</sup> Ag	250 d	50 d	$\beta^-, \gamma$	liver
<sup>109</sup> Cd	463 d	463 d	EC	kidney
<sup>111</sup> In	2.8 d	2.8 d	$\gamma$ , EC	bone marrow, liver
<sup>113m</sup> In	99.5 min	96.6 min	$\gamma$	kidney, gastrointestinal tract
<sup>125</sup> Sb	2.8 yrs	5 d	$\beta^-, \gamma$	bones, liver
<sup>129m</sup> Te	33.6 d	20 d	$\beta^-, \gamma$	bones, kidney
<sup>132</sup> Te	76.3 h	24 h	$\beta^-, \gamma$	bones, kidney
<sup>123</sup> I	13.2 h	13 h	$\gamma$ , EC	thyroid
<sup>125</sup> I	59.4 d	41.8 d	$\gamma$ , EC	thyroid

<b>isotope</b>	<b>physical half-life</b>	<b>effective half-life</b>	<b>emitter</b>	<b>critical organ</b>
$^{129}\text{I}$	$1.6 \times 10^7$ yrs	80 d	$\beta^-$ , $\gamma$	thyroid
$^{131}\text{I}$	8.0 d	7.6 d	$\beta^-$ , $\gamma$	thyroid
$^{132}\text{I}$	2.3 h	2 h	$\beta^-$ , $\gamma$	thyroid
$^{133}\text{I}$	20.8 h	20 h	$\beta^-$ , $\gamma$	thyroid
$^{134}\text{I}$	52 min	52 min	$\beta^-$ , $\gamma$	thyroid
$^{135}\text{I}$	6.6 h	6 h	$\beta^-$ , $\gamma$	thyroid
$^{133}\text{Xe}$	5.3 d	5 min	$\beta^-$ , $\gamma$	whole body
$^{134}\text{Cs}$	2.1 yrs	120 d	$\beta^+$ , $\beta^-$ , $\gamma$	muscles, whole body
$^{136}\text{Cs}$	13.2 d	13 d	$\beta^-$ , $\gamma$	muscles, whole body
$^{137}\text{Cs}$	30.2 yrs	110 d	$\beta^-$ , $\gamma$	muscles, whole body
$^{140}\text{Ba}$	12.8 d	10.7 d	$\beta^-$ , $\gamma$	gastrointestinal tract
$^{138}\text{La}$	$1.1 \times 10^{11}$ yrs	10 yrs	$\beta^-$ , $\gamma$ , EC	liver, bones
$^{141}\text{Ce}$	32.5 d	32 d	$\beta^-$ , $\gamma$	bones, liver
$^{144}\text{Ce}$	284.8 d	280 d	$\beta^-$ , $\gamma$	bones, liver
$^{147}\text{Pm}$	2.6 yrs	2.4 yrs	$\beta^-$ , $\gamma$	bones, liver
$^{147}\text{Sm}$	$1.1 \times 10^{11}$ yrs	10 yrs	$\alpha$	liver, bones
$^{176}\text{Lu}$	$3.8 \times 10^{10}$ yrs	10 yrs	$\beta^-$ , $\gamma$	bones
$^{186}\text{Re}$	89.3 h	48 h	$\beta^-$ , $\gamma$ , EC	muscle tissue
$^{187}\text{Re}$	$5 \times 10^{10}$ yrs	2 d	$\beta^-$	muscle tissue
$^{198}\text{Au}$	2.7 d	1 d	$\beta^-$ , $\gamma$	kidney, gastrointestinal tract
$^{203}\text{Hg}$	46.6 d	11 d	$\beta^-$ , $\gamma$	kidney
$^{201}\text{Tl}$	73.1 h	72 h	$\gamma$ , EC	whole body
$^{202}\text{Tl}$	12.2 d	10 d	$\gamma$ , EC	whole body
$^{208}\text{Tl}$	3.1 min	3 min	$\beta^-$ , $\gamma$	whole body
$^{210}\text{Pb}$	22.3 yrs	1.2 yrs 6.8 yrs	$\beta^-$ , $\gamma$	kidney bones
$^{212}\text{Pb}$	10.6 h	10 h	$\beta^-$ , $\gamma$	bones, liver
$^{212}\text{Bi}$	60.6 min	60 min	$\alpha$ , $\beta^-$ , $\gamma$	kidney
$^{214}\text{Bi}$	19.9 min	19 min	$\alpha$ , $\beta^-$ , $\gamma$	kidney
$^{210}\text{Po}$	138.4 d	31.7 d 66.7 d	$\alpha$ , $\gamma$	kidney lung

<b>isotope</b>	<b>physical half-life</b>	<b>effective half-life</b>	<b>emitter</b>	<b>critical organ</b>
$^{220}\text{Rn}$	55.6 s	55 s	$\alpha, \gamma$	lung
$^{222}\text{Rn}$	3.8 d	5 min	$\alpha, \gamma$	lung
$^{224}\text{Ra}$	3.7 d	3.7 d	$\alpha, \gamma$	bones, bone marrow, lung
$^{226}\text{Ra}$	1600 yrs	41 yrs	$\alpha, \gamma$	bones, bone marrow, lung
$^{228}\text{Ra}$	5.8 yrs	5.7 yrs	$\beta^-, \gamma$	bones, bone marrow, lung
$^{227}\text{Ac}$	21.8 yrs	21 yrs	$\alpha, \beta^-, \gamma$	bones, liver
$^{228}\text{Ac}$	6.1 h	6 h	$\alpha, \beta^-, \gamma$	bones, liver
$^{228}\text{Th}$	1.9 yrs	1.9 yrs	$\alpha, \gamma$	lung, periosteum (bone surface)
$^{230}\text{Th}$	$7.5 \times 10^4$ yrs	25 yrs	$\alpha, \gamma$	lung, periosteum (bone surface)
$^{232}\text{Th}$	$1.4 \times 10^{10}$ yrs	25 yrs	$\alpha, \gamma$	lung, bones
$^{234}\text{Th}$	24.1 d	24 d	$\beta^-, \gamma$	lung, periosteum (bone surface)
$^{231}\text{Pa}$	$3.3 \times 10^4$ yrs	10 yrs	$\alpha, \gamma$	bones
$^{233}\text{U}$	$1.6 \times 10^5$ yrs	variable, $\leq$ 14 yrs	$\alpha, \gamma$	bones, lung, kidney
$^{234}\text{U}$	$2.5 \times 10^5$ yrs	variable, $\leq$ 14 yrs	$\alpha, \gamma, \text{sf}$	bones, lung, kidney
$^{235}\text{U}$	$7 \times 10^8$ yrs	variable, $\leq$ 14 yrs	$\alpha, \gamma, \text{sf}$	bones, lung, kidney
$^{238}\text{U}$	$4.5 \times 10^9$ yrs	variable, $\leq$ 14 yrs	$\alpha, \gamma, \text{sf}$	bones, lung, kidney
$^{237}\text{Np}$	$2.1 \times 10^6$ yrs	variable	$\alpha, \gamma, \text{sf}$	bones, liver
$^{238}\text{Pu}$	87.7 yrs	46.2 yrs	$\alpha, \gamma, \text{sf}$	periosteum (bone surface) liver, lung, blood
$^{239}\text{Pu}$	24110 yrs	100 yrs	$\alpha, \gamma, \text{sf}$	periosteum (bone surface) liver, lung, blood
$^{240}\text{Pu}$	6563 yrs	100 yrs	$\alpha, \gamma, \text{sf}$	periosteum (bone surface) liver, lung, blood
$^{242}\text{Pu}$	$3.8 \times 10^5$ yrs	100 yrs	$\alpha, \gamma, \text{sf}$	periosteum (bone surface) liver, lung, blood
$^{241}\text{Am}$	432 yrs	84 yrs	$\alpha, \gamma, \text{sf}$	bones
$^{242}\text{Cm}$	163 d	162 d	$\alpha, \gamma, \text{sf}$	bones, liver, lung
$^{243}\text{Cm}$	29.1 yrs	15 yrs	$\alpha, \gamma, \text{sf}$	bones, liver, lung
$^{244}\text{Cm}$	18.1 yrs	15 yrs	$\alpha, \gamma, \text{sf}$	bones, liver, lung
$^{249}\text{Bk}$	320 d	316 d	$\alpha, \beta^-, \gamma, \text{sf}$	bones
$^{252}\text{Cf}$	2.6 yrs	2.5 yrs	$\alpha, \gamma, \text{sf}$	bones
$^{253}\text{Es}$	20.5 d	20.5 d	$\alpha, \gamma, \text{sf}$	bones

## Abbreviations

sf – spontaneous fission  
EC – electron capture

## References:

B. Lindskoug,

Manual on early medical treatment of possible radiation injury,  
Safety series no. 47. Recommendations (IAEA, Vienna, 1978);  
Nuclear Instruments and Methods, Vol. 161, issue 1, p. 172 (1979)

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Physicians' Cancer Chemotherapy Drug Manual

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Radiation Safety Office, G-07 Parran Hall, Pittsburgh, USA

[www.radsafe.pitt.edu/ManualTraining/Appendix%20C.htm](http://www.radsafe.pitt.edu/ManualTraining/Appendix%20C.htm)

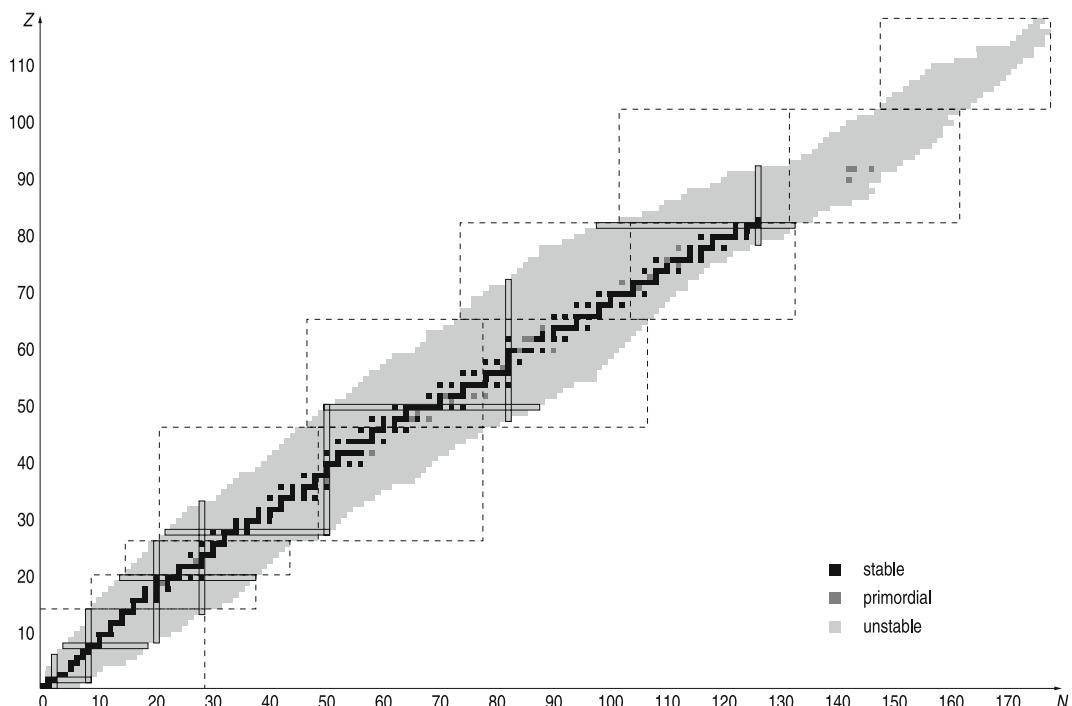
U. Bertsche, Hessisches Ministerium für Umwelt, Wiesbaden,  
Radionuklide in der Umweltüberwachung, Medizin und Technik, (2001)

It has to be mentioned that the values for the effective half-life differ in various publications. Also, the effective half-life varies for different organs and tissues. Therefore the quoted figures just give a rough idea for the effective half-life.

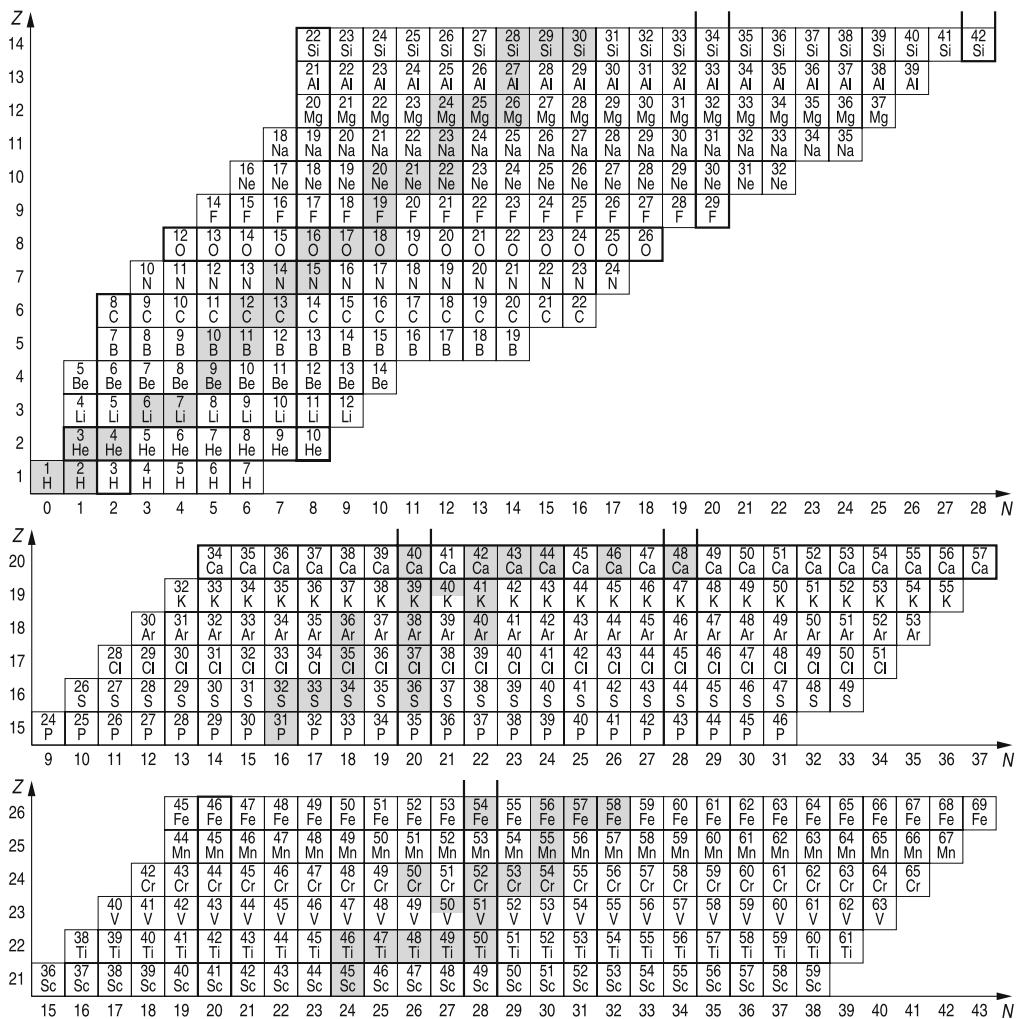
## O Simplified Table of Isotopes and Periodic Table of Elements

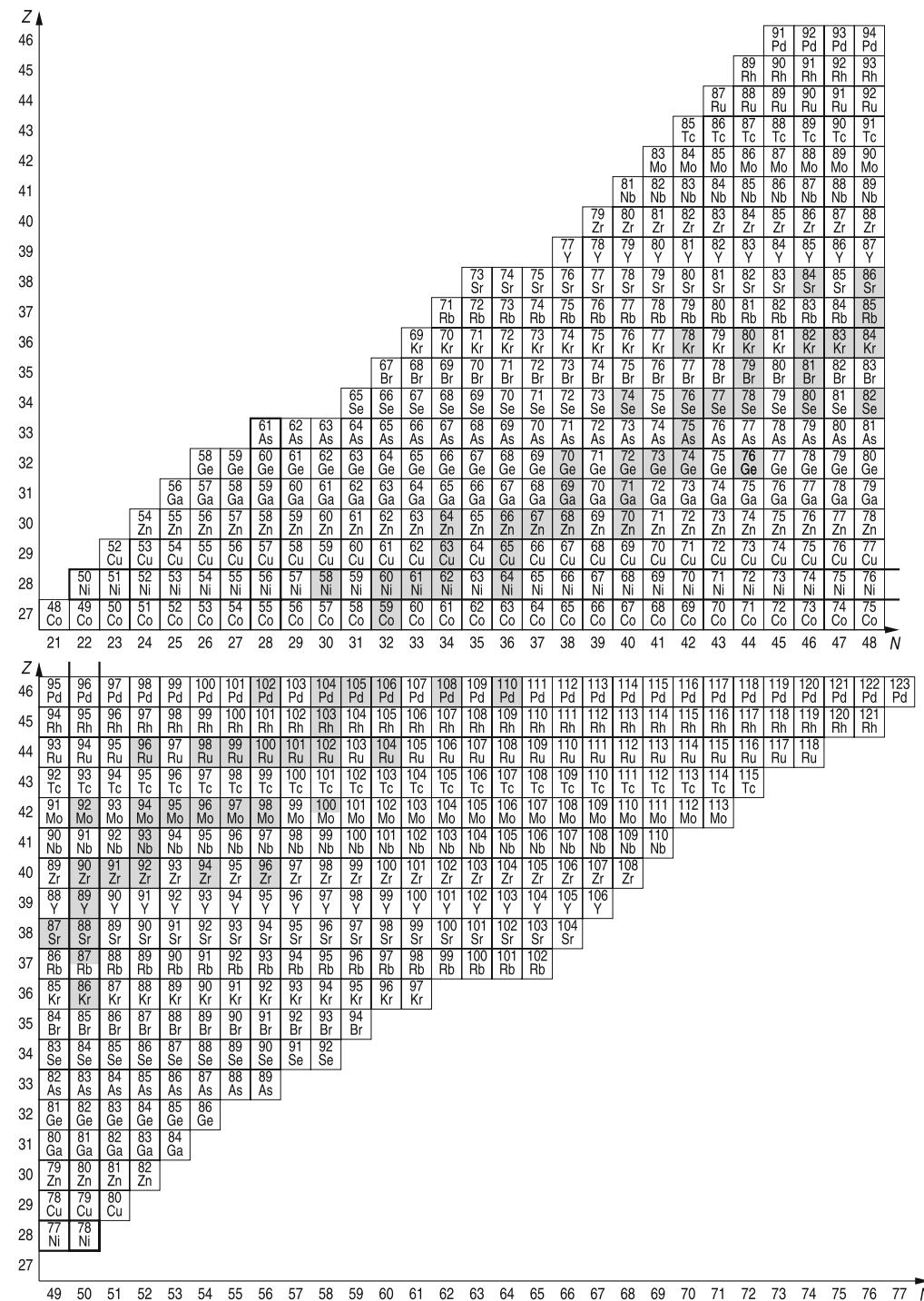
The isotopes (fixed number of protons  $Z$  and variable number of neutrons) of various elements are arranged horizontally. Isotones (fixed number of neutrons  $N$ ) are put vertically.

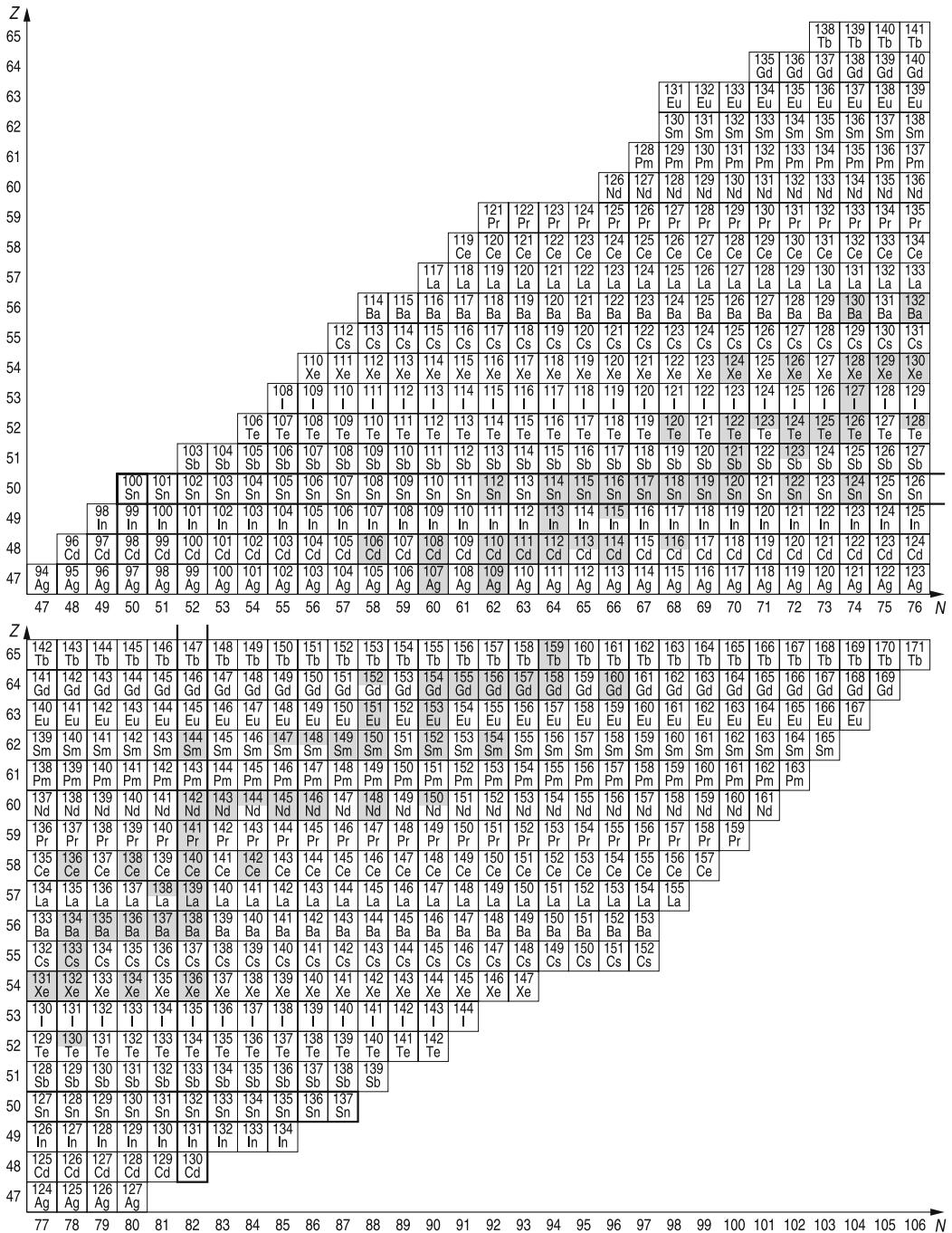
In the overview table below, stable, primordial, and unstable nuclides are displayed with different gray scales, and the cut-out tables are marked by dash-dotted frames; the latter are shown in the order from lighter to heavier isotopes, i.e. from the lower left to the upper right. In the cut-out tables the stable nuclides are highlighted by a light gray background and the primordial ones by such a background in the upper half of their small box. Magic numbers are marked by frames of bold solid lines.

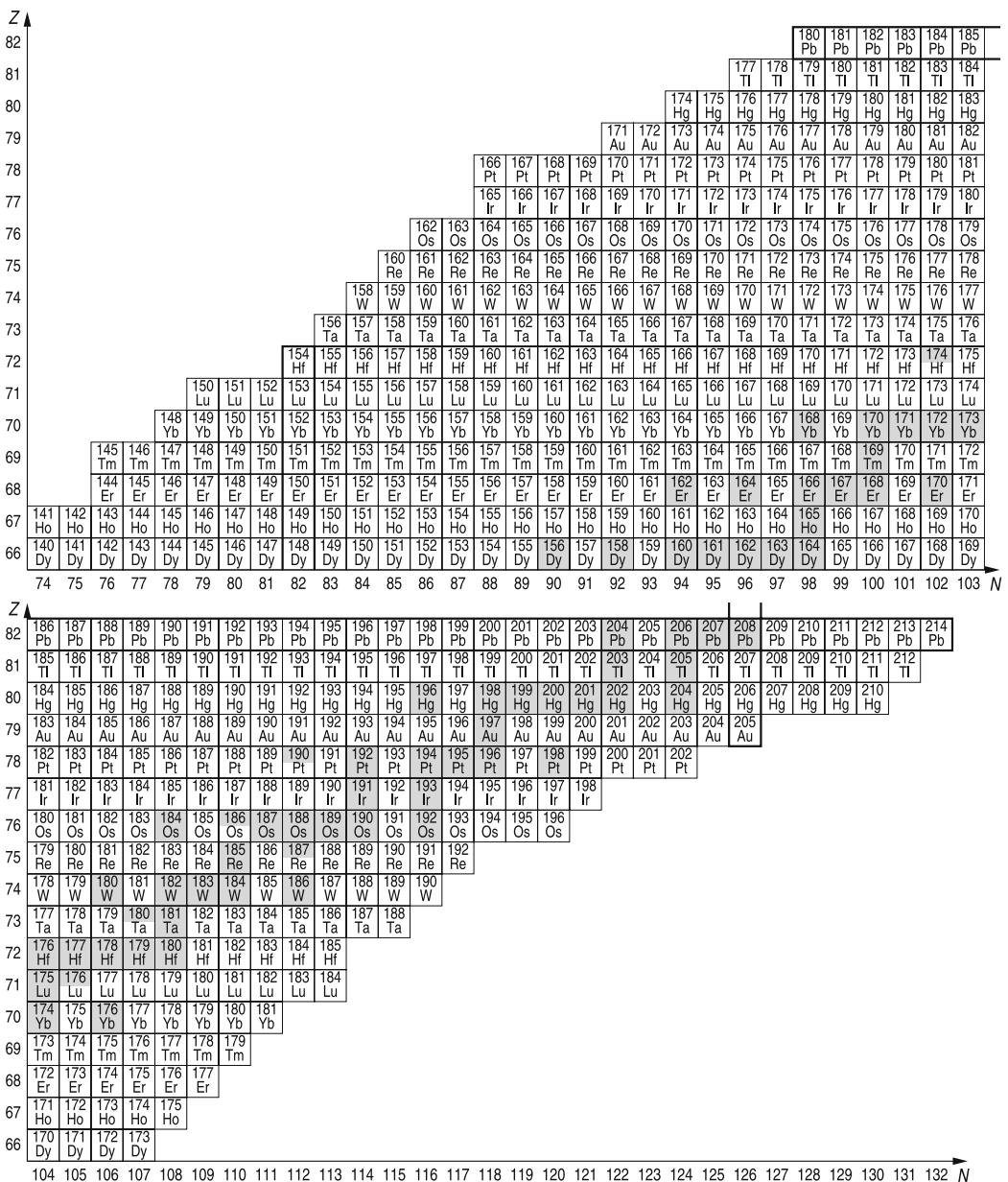


An isotope is said to be stable, if its half-life is larger than  $10^{10}$  yrs, which roughly corresponds to the age of the universe. The mass number is conserved in  $\beta^-$  decays. Such nuclear decays therefore describe transitions in the diagonal (isobars)  $A = Z + N = \text{const}$  ( $\beta^-$ : one isotope to the upper left;  $\beta^+$ : one isotope to the lower right).  $\alpha$  decays change the mass number by 4 units and the nuclear-charge number by 2 units. In the diagram these transitions are obtained by  $\Delta N = \Delta Z = -2$ . Decays by spontaneous fission only occur for elements with  $Z \geq 90$ . The decay by spontaneous fission is often in competition to  $\alpha$  decay.

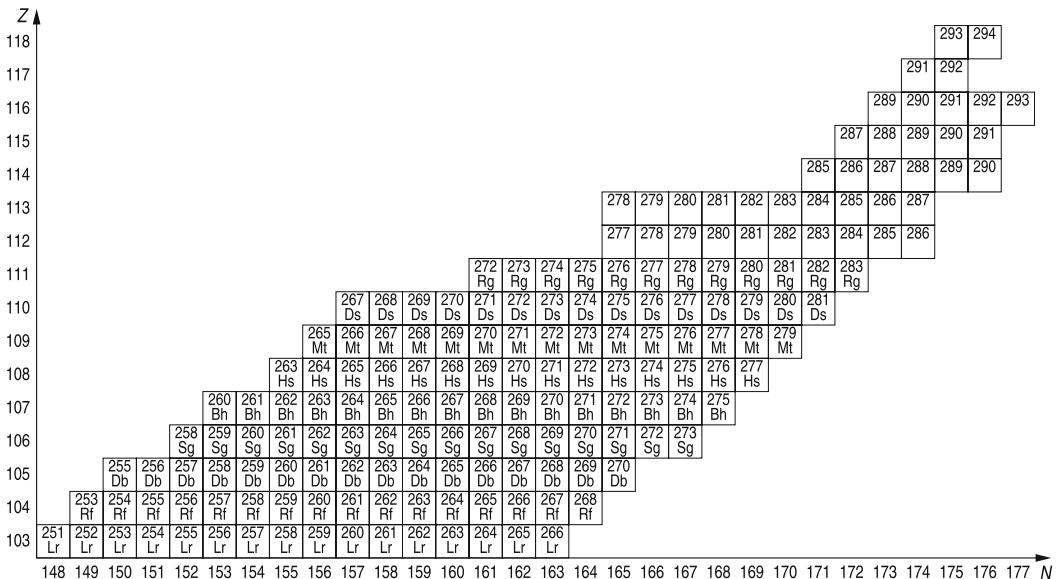








The figure shows a periodic table of elements with atomic number  $Z$  on the y-axis ranging from 83 to 102. The elements are arranged in groups and periods. Notable features include the presence of elements with atomic numbers 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, and 131. The table also includes the element At (Atomic Number 85) and various isotopes of elements like Rn, Fr, Ra, Ac, Th, Pa, and Bi.



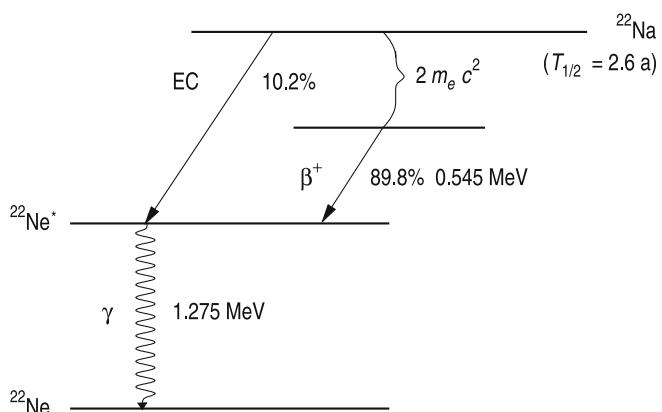
A complete overview of known isotopes is given in “Karlsruher Nuklidkarte” from 2006 (G. Pfennig, H. Klewe-Nebenius, W. Seelmann-Eggebert, Forschungszentrum Karlsruhe 2006). Up-to-date information one finds also under e.g. [www.nucleonica.net](http://www.nucleonica.net).

Group																						
1	H	Ia	IIa	IIIb	IVb	Vb	VIb	VIIb	VIIIb	VIIfb	VIIIfb	VIIfb	IIa	IIb	IIa	IVa	Va	VIa	VIIa			
1.01	1	H																				
1.01	3	Li	4 Be	Beryllium																		
6.94	9.01	Lithium	Beryllium																			
11.01	12 Mg	Magnesium	Sodium																			
22.99	24.31	Potassium	Calciun	Scandium	Titanium	Vanadium	Chromium	23 Ti	24 Cr	25 Mn	26 Fe	27 Cobalt	28 Nickel	29 Copper	30 Zinc	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
39.101	40.08	Rubidium	Strontium	Yttrium	Zirconium	Niobium	Molybdenum	54.94	52.00	53.85	54.94	55.93	56.69	58.35	63.55	65.39	69.72	72.64	74.92	75.96	79.90	83.80
55.47	56.94	Ba	57-71 Lanthanides	72.91	72.91	72.91	72.91	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	
132.91	137.33	Cesium	Barium	Hafnium	Tantalum	Rhenium	Rhenium	105.73	106.95	108.95	108.95	108.95	108.95	108.95	108.95	109.19	110.23	111.27	112.31	113.35	114.39	
187.9	188.88	Radium	Francium	Actinides	Rutherfordium	Dubnium	Seaborgium	106.95	107.95	108.95	109.19	110.23	111.27	112.31	113.35	114.39	115.43	116.47	117.51	118.55	119.59	
223.02	226.03							263.12	262.11	262.11	262.11	262.11	262.11	262.11	262.11	262.11	262.11	262.11	262.11	262.11	262.11	
Lanthanide series	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	72 Hf	73 Erbium	74 Thulium	75 Ytterbium	76 Lutetium	77 Lu	
	138.91	140.12	140.91	144.24	144.91	150.36	151.96	157.25	158.93	162.50	164.93	167.26	168.93	173.04	174.97							
Actinide series	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cf	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Ur	104 Lu	105 Lawrencium	106 Nobelium	107 Mendelevium	108 Curium	109 Californium	110 Americium
	227.03	232.04	231.04	238.03	237.05	243.06	244.06	247.07	247.07	251.08	252.08	257.09	258.10	259.10	262.11							

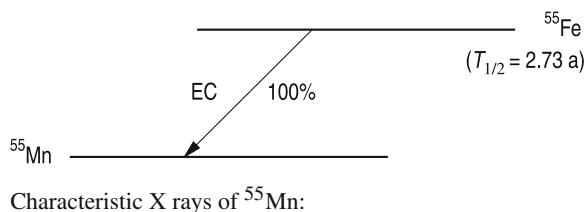
For each element the atomic number (top left) and atomic mass (bottom) is given. The atomic mass is weighted by the isotopic abundance in the Earth's crust.

## P Decay-Level Schemes

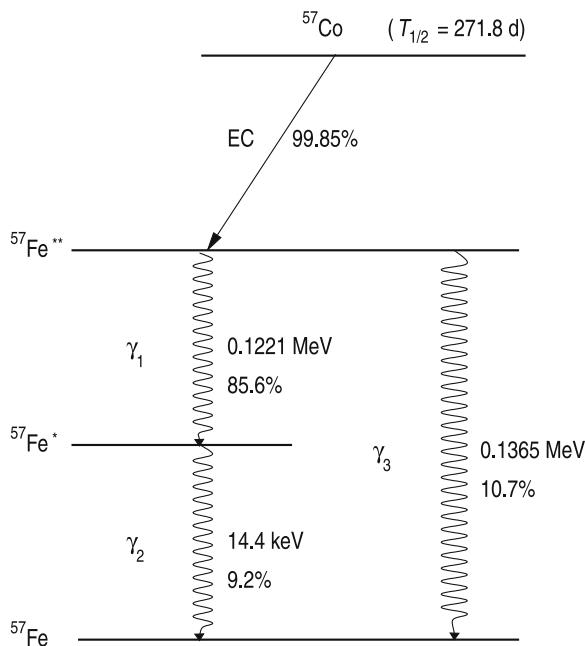
In the following simplified decay-level schemes for some frequently used isotopes in the field of radiation protection are given. For the continuous electron spectra the maximum energies are given. EC stands for electron capture and ‘a’ for annum (year).



**Figure P.1**  
Decay-level scheme of  $^{22}\text{Na}$



**Figure P.2**  
Decay-level scheme of  $^{55}\text{Fe}$



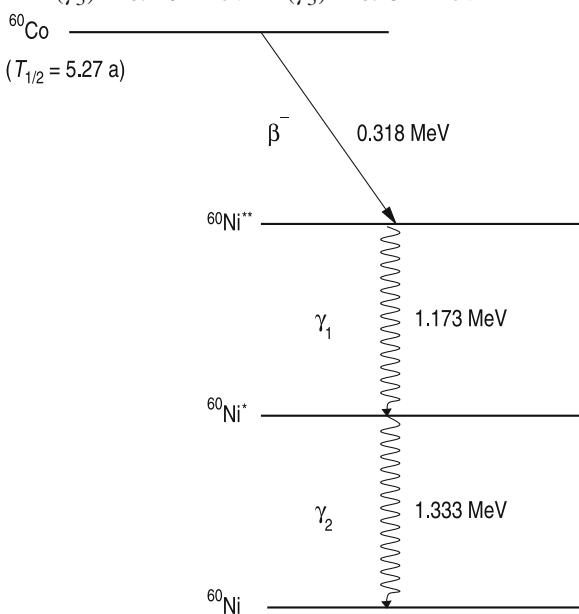
Conversion electrons:

$$K(\gamma_1) = 0.115 \text{ MeV} \quad L(\gamma_1) = 0.121 \text{ MeV}$$

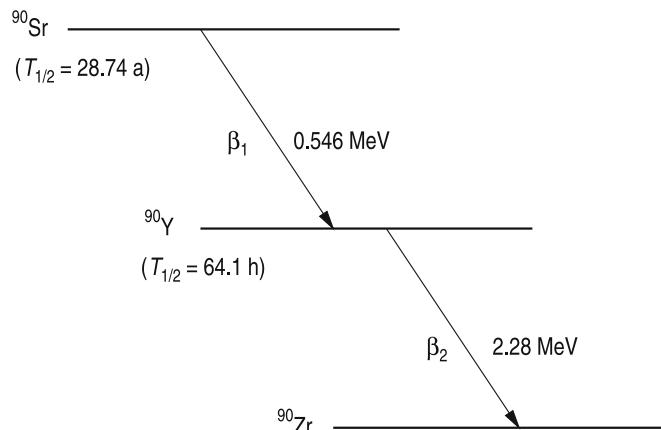
$$K(\gamma_2) = 0.0073 \text{ MeV} \quad L(\gamma_2) = 0.0136 \text{ MeV}$$

$$K(\gamma_3) = 0.1294 \text{ MeV} \quad L(\gamma_3) = 0.1341 \text{ MeV}$$

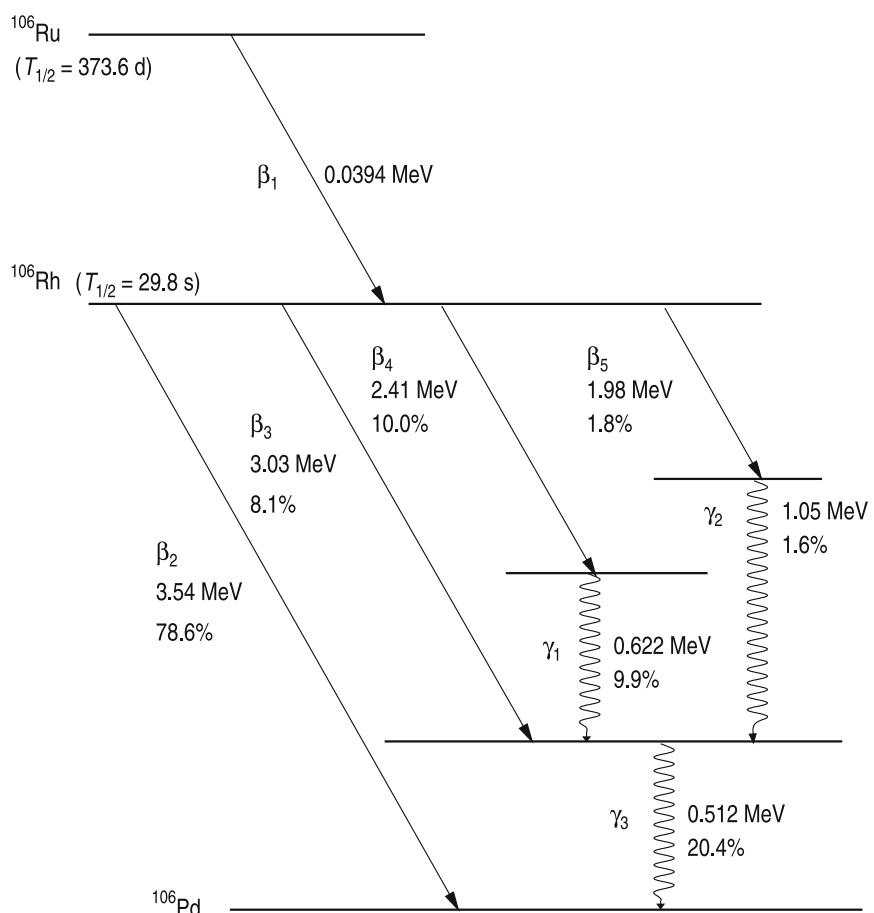
**Figure P.3**  
Decay-level scheme of  $^{57}\text{Co}$



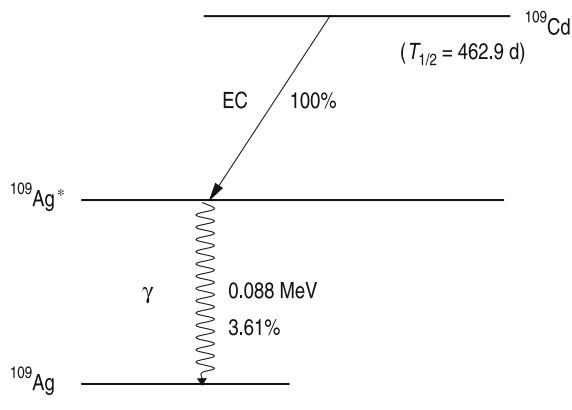
**Figure P.4**  
Decay-level scheme of  $^{60}\text{Co}$



**Figure P.5**  
Decay-level scheme of  $^{90}\text{Sr}$



**Figure P.6**  
Decay-level scheme of  $^{106}\text{Ru}$



Conversion electrons:

$$K(\gamma) = 0.0625 \text{ MeV}$$

$$L(\gamma) = 0.0842 \text{ MeV}$$

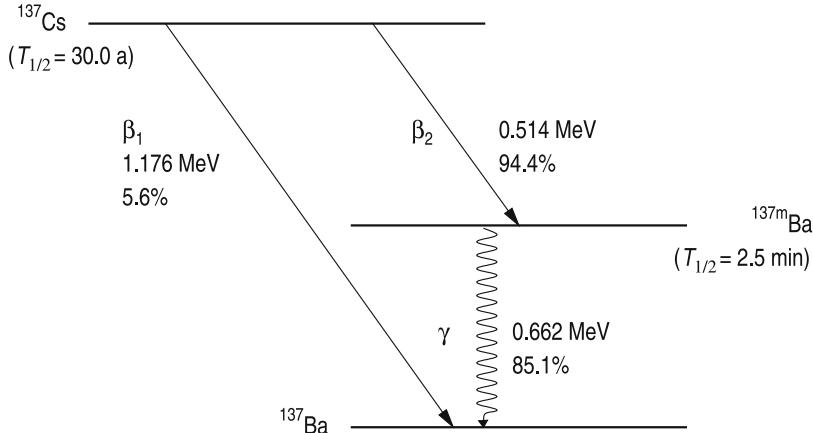
$$M(\gamma) = 0.0873 \text{ MeV}$$

$K_\alpha$  X rays: 0.022 MeV

$K_\beta$  X rays: 0.025 MeV

**Figure P.7**

Decay-level scheme of  $^{109}\text{Cd}$



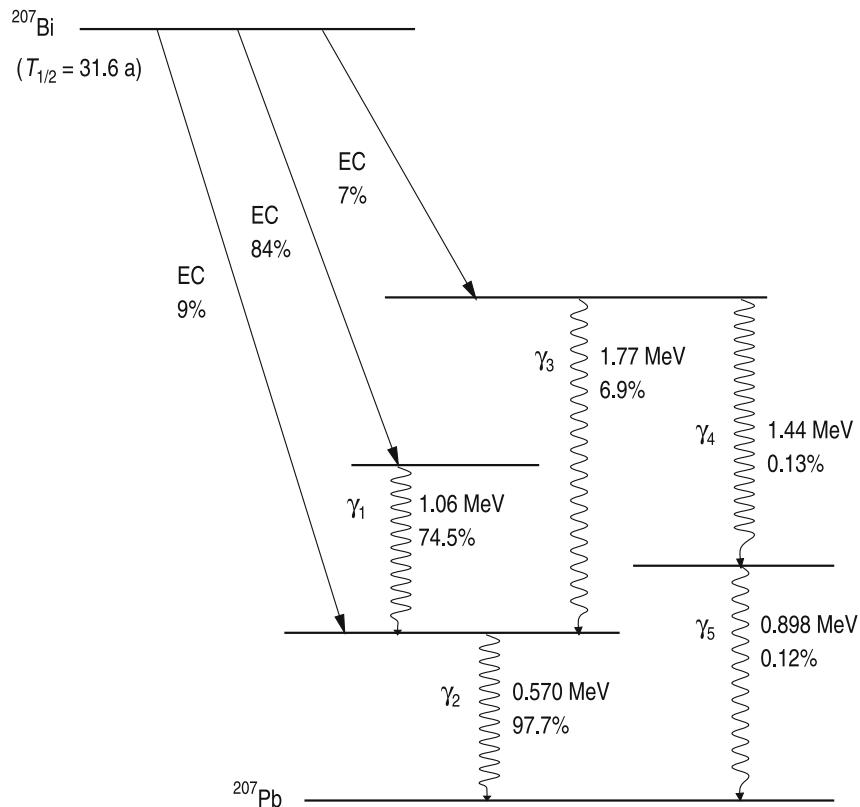
Conversion electrons:

$$K(\gamma) = 0.624 \text{ MeV}$$

$$L(\gamma) = 0.656 \text{ MeV}$$

**Figure P.8**

Decay-level scheme of  $^{137}\text{Cs}$



Conversion electrons:

$$K(\gamma_1) = 0.976 \text{ MeV} \quad L(\gamma_1) = 1.048 \text{ MeV}$$

$$K(\gamma_2) = 0.482 \text{ MeV} \quad L(\gamma_2) = 0.554 \text{ MeV}$$

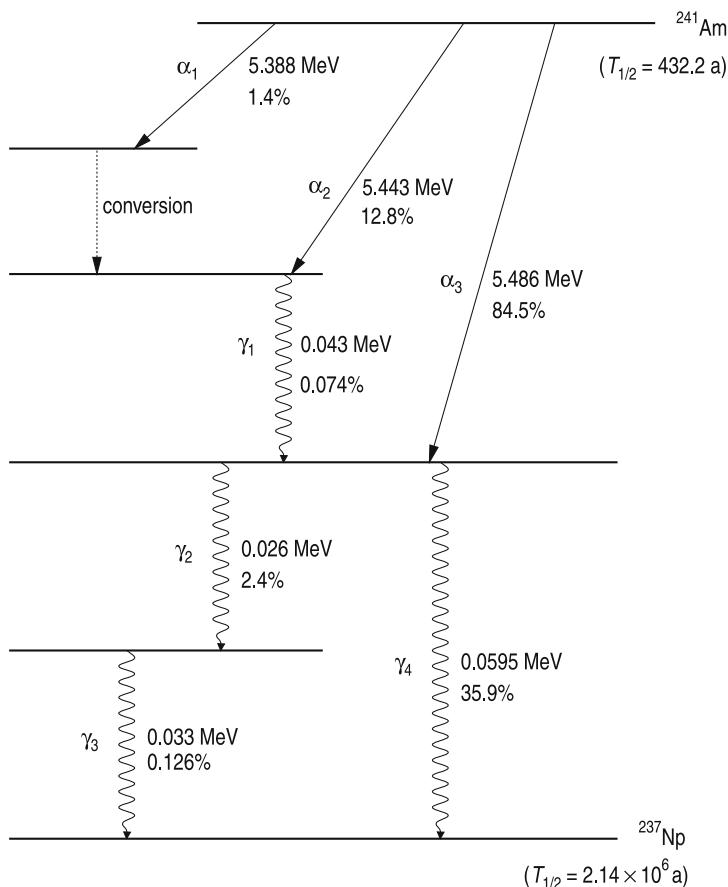
$$K(\gamma_3) = 1.682 \text{ MeV} \quad L(\gamma_3) = 1.754 \text{ MeV}$$

$$K(\gamma_4) = 1.352 \text{ MeV} \quad L(\gamma_4) = 1.424 \text{ MeV}$$

$$K(\gamma_5) = 0.810 \text{ MeV} \quad L(\gamma_5) = 0.882 \text{ MeV}$$

**Figure P.9**

Decay-level scheme of  $^{207}\text{Bi}$



Conversion electrons:

$K(\gamma_i)$  kinematically impossible

$$L(\gamma_1) = 0.0210\text{ MeV}$$

$$L(\gamma_2) = 0.0039\text{ MeV}$$

$$L(\gamma_3) = 0.0108\text{ MeV}$$

$$L(\gamma_4) = 0.0371\text{ MeV}$$

**Figure P.10**  
Decay-level scheme of  $^{241}\text{Am}$

## Q Introduction into the Basics of Mathematics

*“The physicist in preparing for his work needs three things: mathematics, mathematics, and mathematics.”*

*Wilhelm Conrad Röntgen*

Correlations and laws in natural science can most elegantly be represented by diagrams and elementary mathematical functions. The description of physics relations in mere words – like the simple law on the forces between two massive bodies – as it was standard three centuries ago (e.g. in Newton's *Philosophiae Naturalis Principia Mathematica*, 1687), is hard to understand and lacks the precision of mathematical notation. On the other hand, basic mathematical relations are not easily accessible to everyone, and it requires some experience and basic knowledge of getting used to them.

Nature, however, is governed by some natural laws and functions which cannot easily be described in words. Instead they are best represented by simple mathematical formulae. In the following, therefore, some basic concepts are explained, which are relevant for many aspects associated with radiation protection and radioactivity and which allow a precise representation of correlations and laws for data and facts.

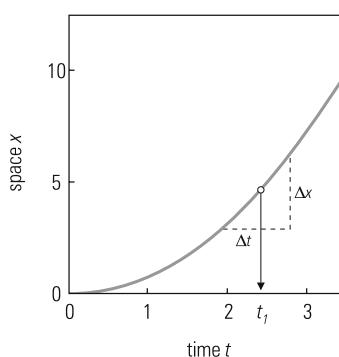
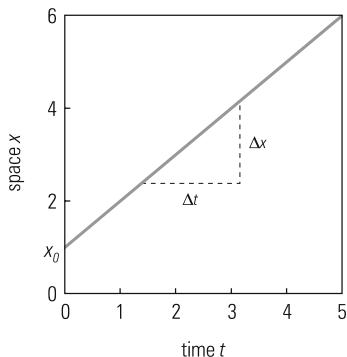
### Q.1 Derivatives and Integrals

The temporal and spatial change of a quantity is called its derivative. This feature will be explained for the example of a path–time diagram. Figure Q.1 shows the uniform motion of some object as a function of space  $x$  and time  $t$ .

The constant slope of this line – expressed by the ratio  $\Delta x / \Delta t$  – is the constant velocity  $v$ . If the velocity is not constant, the current value of the velocity depends on the size of the finite time and space intervals  $\Delta t$  and  $\Delta x$ . Such a non-linear path–time relation is plotted in Fig. Q.2.

**difference quotient**

The ratio  $\Delta x / \Delta t$  for very small values of intervals leads to the concept of the instantaneous velocity at the time  $t_1$ . If the exact value of the velocity at the time  $t_1$  is required, one has to select infinitesimally small space and time intervals. To characterize such infinitesimal intervals Leibniz proposed the notation  $dx/dt$ . The quantity  $dx/dt$  therefore describes the slope of the path–time relation at the



particular time  $t_1$ , which is the instantaneous velocity at the time  $t_1$ . Newton, who independently of Leibniz discovered this ‘calculus’, introduced as notation for the time derivative a dot over the spatial symbol:  $\dot{x}$ . Therefore we have the equivalence

$$\frac{dx}{dt} \equiv \dot{x} . \quad (\text{Q.1})$$

Leibniz’ way to characterize the time derivative by  $dx/dt$  has advanced the development of calculus (differential and integral calculus) substantially in continental Europe, while Newton’s notation using dots on top of quantities – which was kept in England due to Newton’s authority – hindered and delayed the advancement of calculus significantly. This was due to the fact that Leibniz’ notation could be inverted without problems (see integration below), while this turned out to be difficult with the dot over the symbol.

Presently both notations are used only for time derivatives of physical quantities. Of course, both notations are equivalent. Figure Q.2 clearly shows that for a non-linear path–time relation the velocity  $v = dx/dt$  changes with time. The object (e.g. a car starting at a traffic light when it turned green) accelerates from  $t = 0$ , where the acceleration is the change of velocity per time:

$$\text{acceleration } a = \frac{dv}{dt} = \dot{v} . \quad (\text{Q.2})$$

Starting from considerations of the difference quotient, one can derive simple rules for the way how to differentiate special functions. For a polynomial

$$x(t) = a + b t + c t^2 \quad (\text{Q.3})$$

one gets

$$\frac{dx(t)}{dt} = b + 2 c t , \quad (\text{Q.4})$$

**Figure Q.1**  
Relation between space and time  
for a uniform motion

**Figure Q.2**  
Example of a non-linear relation  
between space and time

**notation convention**

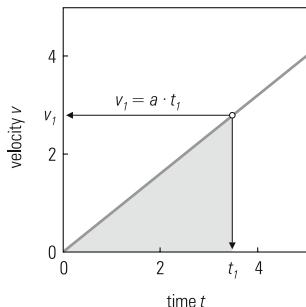
**time derivative**

**acceleration**

as can be easily seen from Figs. Q.1 and Q.2 (the slope of a constant  $a$  is zero, the slope of a linear function  $b t$  is equal to  $b$ , and the slope of a parabola  $c t^2$  is obtained to be  $2 c t$ ).<sup>1</sup>

In general, a power-law relation is differentiated as

$$\frac{d}{dt} t^n = n t^{n-1} . \quad (\text{Q.5})$$



**Figure Q.3**  
Example of a linear velocity–time relation

### integration = determination of an area

### power-law integration

In this rule  $t$  must not necessarily be the time, but it can be any variable.

The inverse of differentiation is the integration. Let us consider the particular velocity–time relation  $v(t) = a t$ , which is the straight line with slope  $a$  as shown in Fig. Q.3.

The integral over the velocity–time relation in the limits from  $t = 0$  to  $t = t_1$  is the area under the curve  $v(t) = a t$  in these limits, i.e. the shaded area. This can be worked out, in this example, from the area of the rectangular triangle with the base along the time axis  $t_1$  and the height  $v_1 = a t_1$  divided by 2,

$$\frac{t_1 a t_1}{2} = \frac{1}{2} a t_1^2 . \quad (\text{Q.6})$$

For this operation one uses as shorthand the integral over the function  $v = a t$  in the limits from  $t = 0$  to  $t = t_1$ .<sup>2</sup>

$$\int_0^{t_1} a t dt = \frac{1}{2} a t^2 \Big|_0^{t_1} = \frac{1}{2} a t_1^2 . \quad (\text{Q.7})$$

The general rule for integrating a polynomial reads:

$$\int_0^{t_1} t^n dt = \frac{t^{n+1}}{n+1} \Big|_0^{t_1} = \frac{t_1^{n+1}}{n+1} . \quad (\text{Q.8})$$

In case of an integration without giving limits the result of the integral is naturally only determined up to a constant, which can only be fixed by the integration limits (boundary conditions):

$$\int t^n dt = \frac{t^{n+1}}{n+1} + \text{const} . \quad (\text{Q.9})$$

---

<sup>1</sup>  $\frac{c(t+\Delta t)^2 - c(t-\Delta t)^2}{\Delta t} = \frac{c(t^2 + t \Delta t + \frac{\Delta t^2}{4}) - c(t^2 - t \Delta t + \frac{\Delta t^2}{4})}{\Delta t} = \frac{2 c t \Delta t}{\Delta t} = 2 c t$

<sup>2</sup> In general, the integral over a linear function between two arbitrary limits  $t_1$  and  $t_2$  is worked out to be:

$$\int_{t_1}^{t_2} a t dt = \frac{1}{2} a t^2 \Big|_{t_1}^{t_2} = \frac{1}{2} a t_2^2 - \frac{1}{2} a t_1^2 = \frac{1}{2} a (t_2^2 - t_1^2) .$$

Formally, the consistency of this prescription can be verified by differentiating the result of the integration on the right-hand side. The differentiation of a constant (in this case the integration constant) gives zero (a constant has no slope), and thus the initial function  $t^n$  is again retrieved.

## Q.2 Exponential Function

In radioactive decay the number of decayed nuclei  $\Delta N$  is proportional to the number of existing nuclei  $N$  and the observation time  $\Delta t$ . Obviously the number of nuclei decreases by decay. This results in a minus sign as in the following relation:

$$\Delta N \sim -N \Delta t . \quad (\text{Q.10})$$

Since the decay rate changes in time, a differential notation is appropriate,

$$dN \sim -N dt . \quad (\text{Q.11})$$

The introduction of a constant of proportionality leads to the identity

$$dN = -\lambda N dt , \quad (\text{Q.12})$$

where  $\lambda$  is the decay constant. Such a relation – one of the most basic differential equations – is solved by the so-called exponential function<sup>3</sup>

$$N = N_0 e^{-\lambda t} . \quad (\text{Q.13})$$

The number  $e$ , first introduced by Leonhard Euler, has the numerical value of  $e = 2.71828\dots$ .

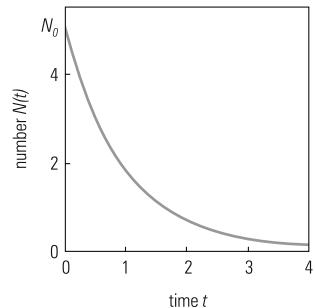
$N_0$  denotes the number of originally existing nuclei, i.e. at  $t = 0$ . An example for the exponential function is plotted in Fig. Q.4. The exponential function describes a large number of natural processes, for example, the attenuation of  $\gamma$  rays in matter or the variation of the atmospheric pressure with altitude. For technical reasons the function  $e^{-\lambda t}$  is occasionally also printed as  $\exp(-\lambda t)$ .

The exponential function has a very remarkable property: the slope of the function  $e^t$ , i.e. its derivative, is also an exponential, that means, it reproduces exactly itself,

$$\frac{d}{dt} e^t = e^t . \quad (\text{Q.14})$$

<sup>3</sup>  $\frac{dN}{N} = -\lambda dt \Rightarrow \int \frac{dN}{N} = -\int \lambda dt \Rightarrow \ln N = -\lambda t + \text{const}$  (see also Eq. (Q.25)).  $e^{\ln N} = N = e^{-\lambda t + \text{const}} = e^{-\lambda t} e^{\text{const}}$ ; boundary condition  $N(t=0) = e^{\text{const}} = N_0 \Rightarrow N = N_0 e^{-\lambda t}$ .

**radioactive decay**



**Figure Q.4**

Example for the exponential variation of a quantity (e.g. decay rate) with time

**properties  
of the exponential function**

It is the only function with this astonishing feature. If there is a parameter  $\alpha$  as factor in the exponent, one has

$$\frac{d}{dt} e^{\alpha t} = \alpha e^{\alpha t} . \quad (\text{Q.15})$$

In the same way the integration of the function  $e^t$  retrieves the exponential function,

$$\int e^t dt = e^t + \text{const} , \quad (\text{Q.16})$$

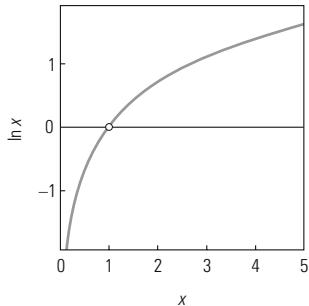
**rules for exponentials** and correspondingly

$$\int e^{\alpha t} dt = \frac{1}{\alpha} e^{\alpha t} + \text{const} . \quad (\text{Q.17})$$

The known rules for powers also apply to exponentials, e.g.

$$e^\alpha e^\beta = e^{\alpha+\beta} . \quad (\text{Q.18})$$

### Q.3 Natural Logarithm



**Figure Q.5**

Graphical representation of a logarithmic variation of a quantity  $x$

**rules for logarithms**

It is desirable that the human senses can perceive a large dynamic range of impressions. Therefore nature, or the evolution of life, has arranged that the sensual perception is proportional to the logarithm of the stimulus (Weber–Fechner law). The logarithm is a weakly rising monotonic function (Fig. Q.5).

The logarithm is the inverse function to the exponential. Equation

$$e^y = x \quad (\text{Q.19})$$

is exactly fulfilled, if

$$y = \ln x . \quad (\text{Q.20})$$

The logarithm was also the basis for slide rules, which have by now been overcome by pocket calculators. Slide rules were based on the property that the logarithm reduces multiplication to addition and powers to multiplication,<sup>4</sup>

<sup>4</sup> If one is willing to memorize a few numbers, one can easily approximate in one's head all logarithms. For the natural logarithm one should memorize  $\ln 2 = 0.6931$  and  $\ln 10 = 2.30$ . Thus, e.g.  $\ln 8000 = \ln 8 + \ln 1000 = 3 \ln 2 + 3 \ln 10 \approx 2.1 + 6.9 = 9.0$ . Analogously, one can proceed with the common logarithm (to the base 10), if one is ready to remember just one value, namely  $\lg 2 = 0.3010$ ; see also Footnote 6.

$$\ln(x \cdot y) = \ln x + \ln y , \quad (\text{Q.21})$$

$$\ln \frac{x}{y} = \ln x - \ln y , \quad (\text{Q.22})$$

$$\ln x^n = n \ln x . \quad (\text{Q.23})$$

A plot of the logarithmic function (Fig. Q.5) shows that its slope is large for small  $x$  and low for large  $x$ . The derivative of the logarithm is obtained to be<sup>5</sup>

$$\frac{d}{dx} \ln x = \frac{1}{x} \quad (\text{see also } \ln x \text{ from Fig. Q.5}). \quad (\text{Q.24})$$

Since the integration is the inverse operation to differentiation, one has

$$\int \frac{1}{x} dx = \ln x + \text{const} . \quad (\text{Q.25})$$

With these rules also the radioactive decay law can now be understood: From

$$N = N_0 e^{-\lambda t} \quad (\text{Q.26})$$

one obtains by differentiating

$$\frac{dN}{dt} = -\lambda N_0 e^{-\lambda t} = -\lambda N , \quad (\text{Q.27})$$

which can be rewritten as

$$dN = -\lambda N dt \quad (\text{Q.28})$$

(compare (Q.12)).

One can easily recognize that the handling of differentials follows the standard and normal rules of calculation.

So far only the natural logarithm (to the base  $e$ ) has been introduced. It is, however, possible to define logarithms also for other bases (e.g. for the base 10: common, Briggs, or decadic logarithm).<sup>6</sup>

The fact that the logarithm linearizes powers can be used to simplify graphical representations. The exponential which characterizes radioactive decay, can be linearized by subdividing the axis that describes the number of nuclei that have not decayed in a logarithmic fashion: Because of

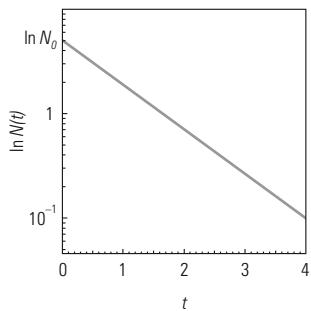
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<sup>5</sup>  $e^y = x ; y = \ln x ; \frac{d \ln x}{dx} = \frac{dy}{dx} = \frac{1}{\frac{dx}{dy}} = \frac{1}{\frac{de^y}{dy}} = \frac{1}{e^y} = \frac{1}{x}$

<sup>6</sup> The natural (or Napierian) logarithm is usually abbreviated as  $\ln x$  ('logarithmus naturalis'); in mathematics it is frequently written as  $\log x$ , even though this notation is not unique. The common, Briggs, or decadic logarithm to the base 10 is mostly denoted by  $\lg x$ . Since the natural logarithm has been introduced as the inverse function to the exponential, one has  $\ln e = 1$ ; analogously  $\lg 10 = 1$ .

### integration and differential of the natural logarithm

### simplifying diagrams by using appropriate scales

**Figure Q.6**

Linearization of an exponential in a semilogarithmic plot

and

$$N = N_0 e^{-\lambda t} \quad (\text{Q.29})$$

$$\ln N = \ln N_0 - \lambda t \quad (\text{Q.30})$$

one obtains a straight line with a slope of  $-\lambda$  and an intersect  $\ln N_0$  (Fig. Q.6).

In an analogous way powers – plotted on double logarithmic paper (log–log paper) – result is straight lines. The power law

$$y = x^n \quad (\text{Q.31})$$

leads to

$$\ln y = n \ln x , \quad (\text{Q.32})$$

which is a straight line with slope  $n$  if both axes are subdivided logarithmically, i.e. if  $\ln y$  is plotted against  $\ln x$ .



"Don't worry, it takes an infinite amount of time to sink completely."

© by Claus Grupen

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