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.

<table>
<thead>
<tr>
<th>isotope $A$</th>
<th>element $Z$</th>
<th>decay type</th>
<th>half-life</th>
<th>$\beta$ resp. $\alpha$ energy (MeV)</th>
<th>$\gamma$ energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$H</td>
<td>$^1$</td>
<td>$\beta^-$</td>
<td>12.3 a</td>
<td>0.0186</td>
<td>no $\gamma$</td>
</tr>
<tr>
<td>$^{2}$Be</td>
<td>$^{11}$Na</td>
<td>EC, $\gamma$</td>
<td>53 d</td>
<td>–</td>
<td>0.48</td>
</tr>
<tr>
<td>$^{10}$Be</td>
<td>$^{14}$C</td>
<td>$\beta^-$</td>
<td>$1.5 \times 10^6$ a</td>
<td>0.56</td>
<td>no $\gamma$</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>$^{22}$Na</td>
<td>$\beta^+$, EC</td>
<td>2.6 a</td>
<td>0.54</td>
<td>1.28</td>
</tr>
<tr>
<td>$^{24}$Na</td>
<td>$^{26}$Al</td>
<td>$\beta^-$, $\gamma$</td>
<td>15.0 h</td>
<td>1.39</td>
<td>1.37</td>
</tr>
<tr>
<td>$^{26}$Al</td>
<td>$^{32}$Si</td>
<td>$\beta^-$</td>
<td>172 a</td>
<td>0.20</td>
<td>no $\gamma$</td>
</tr>
<tr>
<td>$^{32}$Si</td>
<td>$^{32}$P</td>
<td>$\beta^-$</td>
<td>14.2 d</td>
<td>1.71</td>
<td>no $\gamma$</td>
</tr>
<tr>
<td>$^{37}$Ar</td>
<td></td>
<td>EC</td>
<td>35 d</td>
<td>–</td>
<td>no $\gamma$</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>$^{40}$Cr</td>
<td>EC, $\gamma$</td>
<td>27.8 d</td>
<td>–</td>
<td>0.325</td>
</tr>
<tr>
<td>$^{54}$Mn</td>
<td>$^{54}$Mn</td>
<td>EC, $\gamma$</td>
<td>312 d</td>
<td>–</td>
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<tr>
<td>$^{56}$Fe</td>
<td>$^{57}$Co</td>
<td>EC</td>
<td>2.73 a</td>
<td>–</td>
<td>0.006</td>
</tr>
<tr>
<td>$^{57}$Co</td>
<td></td>
<td>EC, $\gamma$</td>
<td>272 d</td>
<td>–</td>
<td>0.122</td>
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<tr>
<td>$^{60}$Co</td>
<td>$^{60}$Co</td>
<td>$\beta^-$, $\gamma$</td>
<td>5.27 a</td>
<td>0.32</td>
<td>1.17 &amp; 1.33</td>
</tr>
<tr>
<td>$^{66}$Ga</td>
<td>$^{66}$Ga</td>
<td>$\beta^+$, EC, $\gamma$</td>
<td>9.4 h</td>
<td>4.15</td>
<td>1.04</td>
</tr>
<tr>
<td>$^{68}$Ga</td>
<td>$^{68}$Ga</td>
<td>$\beta^-$, EC, $\gamma$</td>
<td>68 min</td>
<td>1.88</td>
<td>1.07</td>
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<tr>
<td>$^{85}$Kr</td>
<td>$^{85}$Kr</td>
<td>$\beta^-$, $\gamma$</td>
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<td>0.67</td>
<td>0.52</td>
</tr>
<tr>
<td>$^{89}$Sr</td>
<td>$^{89}$Sr</td>
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<td>51 d</td>
<td>1.49</td>
<td>no $\gamma$</td>
</tr>
<tr>
<td>$^{90}$Sr</td>
<td>$^{90}$Y</td>
<td>$\beta^-$</td>
<td>28.7 a</td>
<td>0.55</td>
<td>no $\gamma$</td>
</tr>
<tr>
<td>$^{90}$Y</td>
<td>$^{99m}$Tc</td>
<td>$\beta^-$</td>
<td>64 h</td>
<td>2.28</td>
<td>no $\gamma$</td>
</tr>
<tr>
<td>$^{99m}$Tc</td>
<td></td>
<td>$\gamma$</td>
<td>6 h</td>
<td>–</td>
<td>0.140</td>
</tr>
<tr>
<td>isotope</td>
<td>decay type</td>
<td>half-life</td>
<td>$\beta$ resp. $\alpha$ energy (MeV)</td>
<td>$\gamma$ energy (MeV)</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
<td>-----------</td>
<td>---------------------------------</td>
<td>----------------------</td>
<td></td>
</tr>
<tr>
<td>$^{106}<em>{44}$Ru $\rightarrow$ $^{106}</em>{45}$Rh</td>
<td>$\beta^-$</td>
<td>1.0 a</td>
<td>0.04</td>
<td>no $\gamma$</td>
<td></td>
</tr>
<tr>
<td>$^{112}_{47}$Ag</td>
<td>$\beta^-, \gamma$</td>
<td>30 s</td>
<td>3.54</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>$^{109}_{48}$Cd $\rightarrow$</td>
<td>EC</td>
<td>1.27 a</td>
<td>–</td>
<td>no $\gamma$</td>
<td></td>
</tr>
<tr>
<td>$^{109m}_{47}$Ag</td>
<td>$\gamma$</td>
<td>40 s</td>
<td>–</td>
<td>0.088</td>
<td></td>
</tr>
<tr>
<td>$^{113}_{50}$Sn</td>
<td>EC, $\gamma$</td>
<td>115 d</td>
<td>–</td>
<td>0.392</td>
<td></td>
</tr>
<tr>
<td>$^{132}_{52}$Te</td>
<td>$\beta^-, \gamma$</td>
<td>77 h</td>
<td>0.22</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>$^{125}_{53}$I</td>
<td>EC, $\gamma$</td>
<td>60 d</td>
<td>–</td>
<td>0.035</td>
<td></td>
</tr>
<tr>
<td>$^{129}_{53}$I</td>
<td>$\beta^-, \gamma$</td>
<td>$1.6 \times 10^7$ a</td>
<td>0.15</td>
<td>0.038</td>
<td></td>
</tr>
<tr>
<td>$^{131}_{53}$I</td>
<td>$\beta^-, \gamma$</td>
<td>8.05 d</td>
<td>0.61</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>$^{133}_{54}$Xe</td>
<td>$\beta^-, \gamma$</td>
<td>5.24 d</td>
<td>0.35</td>
<td>0.08</td>
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</tr>
<tr>
<td>$^{134}_{55}$Cs</td>
<td>$\beta^-, \beta^+, \gamma$</td>
<td>2.06 a</td>
<td>0.65</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td>$^{137}_{55}$Cs $\rightarrow$</td>
<td>$\beta^-$</td>
<td>30 a</td>
<td>0.51 &amp; 1.18</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td>$^{137m}_{56}$Ba</td>
<td>$\gamma$</td>
<td>2.6 min</td>
<td>–</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td>$^{133}_{50}$Ba</td>
<td>EC, $\gamma$</td>
<td>10.5 a</td>
<td>–</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>$^{140}_{57}$La</td>
<td>$\beta^-, \gamma$</td>
<td>40.2 h</td>
<td>1.34</td>
<td>1.60</td>
<td></td>
</tr>
<tr>
<td>$^{144}_{58}$Ce $\rightarrow$</td>
<td>$\beta^-, \gamma$</td>
<td>285 d</td>
<td>0.32</td>
<td>0.13</td>
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</tr>
<tr>
<td>$^{144}_{59}$Pr</td>
<td>$\beta^-, \gamma$</td>
<td>17.5 min</td>
<td>3.12</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>$^{144}_{60}$Nd</td>
<td>$\alpha$</td>
<td>$2.3 \times 10^{15}$ a</td>
<td>1.80</td>
<td>no $\gamma$</td>
<td></td>
</tr>
<tr>
<td>$^{152}_{63}$Eu</td>
<td>EC, $\beta^+, \gamma$</td>
<td>13.5 a</td>
<td>0.68</td>
<td>0.122</td>
<td></td>
</tr>
<tr>
<td>$^{192}_{77}$Ir</td>
<td>EC, $\beta^-, \gamma$</td>
<td>74 d</td>
<td>0.67</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>$^{198}_{79}$Au</td>
<td>$\beta^-, \gamma$</td>
<td>2.7 d</td>
<td>0.96</td>
<td>0.41</td>
<td></td>
</tr>
<tr>
<td>$^{200}_{81}$TI</td>
<td>$\beta^-$, EC</td>
<td>3.78 a</td>
<td>0.76</td>
<td>no $\gamma$</td>
<td></td>
</tr>
<tr>
<td>$^{207}_{83}$Bi</td>
<td>EC, $\gamma$</td>
<td>31.6 a</td>
<td>0.48</td>
<td>0.57</td>
<td></td>
</tr>
<tr>
<td>$^{222}_{86}$Rn $\rightarrow$</td>
<td>$\alpha$, $\gamma$</td>
<td>3.8 d</td>
<td>5.48</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>$^{218}_{84}$Po $\rightarrow$</td>
<td>$\alpha$, $\beta^-$</td>
<td>3.1 min</td>
<td>$\alpha$: 6.00</td>
<td>no $\gamma$</td>
<td></td>
</tr>
<tr>
<td>$^{214}_{82}$Pb</td>
<td>$\beta^-, \gamma$</td>
<td>26.8 min</td>
<td>0.73</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>$^{214}_{83}$Bi</td>
<td>$\beta^-, \gamma$</td>
<td>19.9 min</td>
<td>1.51</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td>$^{226}_{88}$Ra</td>
<td>$\alpha$, $\gamma$</td>
<td>1600 a</td>
<td>4.78</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>$^{238}_{90}$Th</td>
<td>$\alpha$, $\gamma$</td>
<td>1.9 a</td>
<td>5.42</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>$^{234}_{92}$U</td>
<td>$\alpha$, $\gamma$</td>
<td>$2.5 \times 10^5$ a</td>
<td>4.77</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>isotope $^{A}_{Z}$ element</td>
<td>decay type</td>
<td>half-life</td>
<td>$\beta$ resp. $\alpha$ energy (MeV)</td>
<td>$\gamma$ energy (MeV)</td>
<td></td>
</tr>
<tr>
<td>--------------------------</td>
<td>------------</td>
<td>-----------</td>
<td>----------------------------------</td>
<td>------------------</td>
<td></td>
</tr>
<tr>
<td>$^{235}_{92}$U</td>
<td>$\alpha$, $\gamma$</td>
<td>$7.1 \times 10^8$ a</td>
<td>4.40</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>$^{238}_{92}$U</td>
<td>$\alpha$, $\gamma$</td>
<td>$4.5 \times 10^9$ a</td>
<td>4.20</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>$^{239}_{94}$Pu</td>
<td>$\alpha$, $\gamma$</td>
<td>24 110 a</td>
<td>5.15</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>$^{240}_{94}$Pu</td>
<td>$\alpha$, $\gamma$</td>
<td>6564 a</td>
<td>5.16</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>$^{241}_{95}$Am</td>
<td>$\alpha$, $\gamma$</td>
<td>432 a</td>
<td>5.49</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>$^{252}_{98}$Cf</td>
<td>$\alpha$, $\gamma$</td>
<td>2.6 a</td>
<td>6.11</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>$^{252}_{100}$Fm</td>
<td>$\alpha$, $\gamma$</td>
<td>25 h</td>
<td>7.05</td>
<td>0.096</td>
<td></td>
</tr>
<tr>
<td>$^{268}_{109}$Mt</td>
<td>$\alpha$</td>
<td>70 ms</td>
<td>10.70</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>

**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

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 $A_i^{\text{max}}$ are handled in a laboratory, the following condition must be fulfilled:

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

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

<table>
<thead>
<tr>
<th>radioisotope</th>
<th>exemption limit</th>
<th>specific activity in Bq/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{3}\text{H}$</td>
<td>$10^9$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>$^{7}\text{Be}$</td>
<td>$10^7$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>$^{14}\text{C}$</td>
<td>$10^7$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>$^{24}\text{Na}$</td>
<td>$10^5$</td>
<td>10</td>
</tr>
<tr>
<td>$^{32}\text{P}$</td>
<td>$10^5$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>$^{40}\text{K}^*$</td>
<td>$10^6$</td>
<td>$10^2$</td>
</tr>
<tr>
<td>$^{54}\text{Mn}$</td>
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<td>10</td>
</tr>
<tr>
<td>$^{55}\text{Fe}$</td>
<td>$10^6$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>$^{57}\text{Co}$</td>
<td>$10^6$</td>
<td>$10^2$</td>
</tr>
<tr>
<td>$^{60}\text{Co}$</td>
<td>$10^5$</td>
<td>10</td>
</tr>
<tr>
<td>radioisotope</td>
<td>exemption limit activity in Bq</td>
<td>specific activity in Bq/g</td>
</tr>
<tr>
<td>-------------</td>
<td>-------------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>$^{82}_{35}$Br</td>
<td>$10^6$</td>
<td>10</td>
</tr>
<tr>
<td>$^{89}_{38}$Sr</td>
<td>$10^6$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>$^{90}_{38}$Sr$^\dagger$</td>
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<td>$10^2$</td>
</tr>
<tr>
<td>$^{99m}_{43}$Tc</td>
<td>$10^7$</td>
<td>$10^2$</td>
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<tr>
<td>$^{106}_{44}$Ru$^\dagger$</td>
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<td>$10^2$</td>
</tr>
<tr>
<td>$^{110m}_{47}$Ag</td>
<td>$10^6$</td>
<td>10</td>
</tr>
<tr>
<td>$^{109}_{48}$Cd$^\dagger$</td>
<td>$10^6$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>$^{125}_{53}$I</td>
<td>$10^6$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>$^{129}_{53}$I</td>
<td>$10^5$</td>
<td>$10^2$</td>
</tr>
<tr>
<td>$^{131}_{53}$I</td>
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<td>$10^2$</td>
</tr>
<tr>
<td>$^{134}_{55}$Cs</td>
<td>$10^4$</td>
<td>10</td>
</tr>
<tr>
<td>$^{137}_{55}$Cs$^\dagger$</td>
<td>$10^4$</td>
<td>10</td>
</tr>
<tr>
<td>$^{133}_{56}$Ba</td>
<td>$10^6$</td>
<td>$10^2$</td>
</tr>
<tr>
<td>$^{152}_{63}$Eu</td>
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</tr>
<tr>
<td>$^{197}_{80}$Hg</td>
<td>$10^7$</td>
<td>$10^2$</td>
</tr>
<tr>
<td>$^{204}_{81}$Tl</td>
<td>$10^4$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>$^{214}_{82}$Pb</td>
<td>$10^6$</td>
<td>$10^2$</td>
</tr>
<tr>
<td>$^{207}_{83}$Bi</td>
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</tr>
<tr>
<td>$^{210}_{84}$Po</td>
<td>$10^4$</td>
<td>10</td>
</tr>
<tr>
<td>$^{220}_{86}$Rn$^\dagger$</td>
<td>$10^7$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>$^{222}_{86}$Rn$^\dagger$</td>
<td>$10^8$</td>
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</tr>
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<td>$^{226}_{88}$Ra$^\dagger$</td>
<td>$10^4$</td>
<td>10</td>
</tr>
<tr>
<td>$^{227}_{89}$Ac$^\dagger$</td>
<td>$10^3$</td>
<td>0.1</td>
</tr>
<tr>
<td>$^{232}_{90}$Th$^\dagger$</td>
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<td>10</td>
</tr>
<tr>
<td>$^{233}_{92}$U</td>
<td>$10^4$</td>
<td>10</td>
</tr>
<tr>
<td>$^{235}_{92}$U$^\dagger$</td>
<td>$10^4$</td>
<td>10</td>
</tr>
<tr>
<td>$^{238}_{92}$U$^\dagger$</td>
<td>$10^4$</td>
<td>10</td>
</tr>
<tr>
<td>$^{239}_{94}$Pu</td>
<td>$10^4$</td>
<td>1</td>
</tr>
<tr>
<td>$^{240}_{94}$Pu</td>
<td>$10^3$</td>
<td>1</td>
</tr>
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</table>
### Exemption Limits for Absolute and Specific Activities

<table>
<thead>
<tr>
<th>Radioisotope</th>
<th>Exemption Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Activity in Bq</td>
</tr>
<tr>
<td>$^{241}_{95}$Am</td>
<td>$10^4$</td>
</tr>
<tr>
<td>$^{244}_{96}$Cm</td>
<td>$10^4$</td>
</tr>
<tr>
<td>$^{252}_{98}$Cf</td>
<td>$10^4$</td>
</tr>
</tbody>
</table>

* 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.

<table>
<thead>
<tr>
<th>radioisotope</th>
<th>maximum permitted activity concentration in air in Bq/m³</th>
<th>maximum permitted activity concentration in water in Bq/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{3}$H</td>
<td>$10^2$</td>
<td>$10^7$</td>
</tr>
<tr>
<td>$^{4}$Be</td>
<td>$6 \times 10^2$</td>
<td>$5 \times 10^6$</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>6</td>
<td>$6 \times 10^5$</td>
</tr>
<tr>
<td>$^{24}$Na</td>
<td>90</td>
<td>$3 \times 10^5$</td>
</tr>
<tr>
<td>$^{32}$P</td>
<td>1</td>
<td>$3 \times 10^4$</td>
</tr>
<tr>
<td>$^{42}$K</td>
<td>$2 \times 10^2$</td>
<td>$2 \times 10^5$</td>
</tr>
<tr>
<td>$^{54}$Mn</td>
<td>20</td>
<td>$2 \times 10^5$</td>
</tr>
<tr>
<td>$^{55}$Fe</td>
<td>20</td>
<td>$10^5$</td>
</tr>
<tr>
<td>$^{57}$Co</td>
<td>30</td>
<td>$3 \times 10^5$</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>1</td>
<td>$2 \times 10^4$</td>
</tr>
<tr>
<td>$^{82}$Br</td>
<td>50</td>
<td>$10^5$</td>
</tr>
<tr>
<td>$^{89}$Sr</td>
<td>4</td>
<td>$3 \times 10^4$</td>
</tr>
<tr>
<td>$^{90}$Sr</td>
<td>0.1</td>
<td>$4 \times 10^3$</td>
</tr>
</tbody>
</table>
### Maximum Permitted Activity Concentrations Discharged from Radiation Areas

<table>
<thead>
<tr>
<th>radioisotope</th>
<th>maximum permitted activity concentration in air in Bq/m³</th>
<th>in water in Bq/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{99m}_{43}$Tc</td>
<td>$2 \times 10^3$</td>
<td>$4 \times 10^6$</td>
</tr>
<tr>
<td>$^{106}_{44}$Ru</td>
<td>0.6</td>
<td>$10^4$</td>
</tr>
<tr>
<td>$^{110m}_{47}$Ag</td>
<td>1</td>
<td>$4 \times 10^4$</td>
</tr>
<tr>
<td>$^{109}_{48}$Cd</td>
<td>4</td>
<td>$4 \times 10^4$</td>
</tr>
<tr>
<td>$^{125}_{53}$I</td>
<td>0.5</td>
<td>$2 \times 10^4$</td>
</tr>
<tr>
<td>$^{129}_{53}$I</td>
<td>0.03</td>
<td>$4 \times 10^3$</td>
</tr>
<tr>
<td>$^{131}_{53}$I</td>
<td>0.5</td>
<td>$5 \times 10^3$</td>
</tr>
<tr>
<td>$^{134}_{55}$Cs</td>
<td>2</td>
<td>$2 \times 10^4$</td>
</tr>
<tr>
<td>$^{137}_{55}$Cs</td>
<td>0.9</td>
<td>$3 \times 10^4$</td>
</tr>
<tr>
<td>$^{133}_{56}$Ba</td>
<td>4</td>
<td>$4 \times 10^4$</td>
</tr>
<tr>
<td>$^{152}_{63}$Eu</td>
<td>0.9</td>
<td>$5 \times 10^4$</td>
</tr>
<tr>
<td>$^{197}_{80}$Hg</td>
<td>$10^2$</td>
<td>$4 \times 10^5$</td>
</tr>
<tr>
<td>$^{201}_{81}$Tl</td>
<td>10</td>
<td>$7 \times 10^4$</td>
</tr>
<tr>
<td>$^{214}_{82}$Pb</td>
<td>2</td>
<td>$3 \times 10^5$</td>
</tr>
<tr>
<td>$^{207}_{84}$Bi</td>
<td>1</td>
<td>$9 \times 10^4$</td>
</tr>
<tr>
<td>$^{210}_{84}$Po</td>
<td>0.008</td>
<td>30</td>
</tr>
<tr>
<td>$^{226}_{88}$Ra</td>
<td>0.004</td>
<td>$2 \times 10^2$</td>
</tr>
<tr>
<td>$^{227}_{89}$Ac</td>
<td>$7 \times 10^{-5}$</td>
<td>30</td>
</tr>
<tr>
<td>$^{232}_{90}$Th</td>
<td>$3 \times 10^{-4}$</td>
<td>$2 \times 10^2$</td>
</tr>
<tr>
<td>$^{233}_{92}$U</td>
<td>0.004</td>
<td>$2 \times 10^3$</td>
</tr>
<tr>
<td>$^{235}_{92}$U</td>
<td>0.004</td>
<td>$3 \times 10^3$</td>
</tr>
<tr>
<td>$^{238}_{92}$U</td>
<td>0.005</td>
<td>$3 \times 10^3$</td>
</tr>
<tr>
<td>$^{239}_{94}$Pu</td>
<td>$3 \times 10^{-4}$</td>
<td>$2 \times 10^2$</td>
</tr>
<tr>
<td>$^{240}_{94}$Pu</td>
<td>$3 \times 10^{-4}$</td>
<td>$2 \times 10^2$</td>
</tr>
<tr>
<td>$^{241}_{95}$Am</td>
<td>$4 \times 10^{-4}$</td>
<td>$2 \times 10^2$</td>
</tr>
<tr>
<td>$^{244}_{96}$Cm</td>
<td>$6 \times 10^{-4}$</td>
<td>$3 \times 10^2$</td>
</tr>
<tr>
<td>$^{252}_{98}$Cf</td>
<td>0.002</td>
<td>$2 \times 10^2$</td>
</tr>
</tbody>
</table>

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

\[ \sum_{i=1}^{N} \frac{\tilde{C}_{i,a}}{C_i} \leq 1 \]

must be respected, where

- \( C_i \) is the maximum permitted activity concentration
- \( \tilde{C}_{i,a} \) the actual released average annual activity concentration.
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 ($\leq 10 \mu$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.

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

* 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.

<table>
<thead>
<tr>
<th>radioisotope</th>
<th>surface contamination in Bq/cm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$H, $^7$Be, $^{14}$C</td>
<td>100</td>
</tr>
<tr>
<td>$^{18}$F, $^{24}$Na, $^{38}$Cl</td>
<td>1</td>
</tr>
<tr>
<td>$^{54}$Mn, $^{60}$Co, $^{90}$Sr</td>
<td>1</td>
</tr>
<tr>
<td>$^{64}$Cu, $^{76}$As, $^{75}$Se</td>
<td>10</td>
</tr>
<tr>
<td>$^{99m}$Tc, $^{105}$Rh, $^{106}$Ru</td>
<td>10</td>
</tr>
<tr>
<td>$^{114}$Ag, $^{109}$Cd, $^{99}$Tc</td>
<td>100</td>
</tr>
<tr>
<td>$^{125}$I, $^{131}$I, $^{129}$Cs</td>
<td>10</td>
</tr>
<tr>
<td>$^{134}$Cs, $^{137}$Cs, $^{140}$Ba</td>
<td>1</td>
</tr>
<tr>
<td>$^{152}$Eu, $^{154}$Eu, $^{177}$Ir</td>
<td>1</td>
</tr>
<tr>
<td>$^{204}$Tl, $^{197}$Pt, $^{210}$Bi</td>
<td>100</td>
</tr>
<tr>
<td>$^{226}$Ra, $^{227}$Ac, $^{233}$U</td>
<td>1</td>
</tr>
<tr>
<td>$^{239}$pu, $^{240}$Pu, $^{252}$Cf</td>
<td>0.1</td>
</tr>
<tr>
<td>$^{248}$Cm</td>
<td>0.01</td>
</tr>
<tr>
<td>$\beta$ emitter or EC emitter$^1$ with $E_{e\max} &lt; 0.2$ MeV</td>
<td>100</td>
</tr>
<tr>
<td>$\beta$ or $\gamma$ emitter in general</td>
<td>1</td>
</tr>
<tr>
<td>$\alpha$ emitter or radioisotopes from spontaneous fission</td>
<td>0.1</td>
</tr>
</tbody>
</table>
In case of surface contaminations by different isotopes the following condition must be fulfilled:

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

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

\footnote{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.

<table>
<thead>
<tr>
<th>controlled area</th>
<th>surveyed area</th>
</tr>
</thead>
<tbody>
<tr>
<td>exclusion area</td>
<td>6–20 mSv/yr</td>
</tr>
<tr>
<td>&gt; 3 mSv/h</td>
<td>1–6 mSv/yr</td>
</tr>
<tr>
<td>radiation-exposed workers (2000 h/yr)</td>
<td></td>
</tr>
<tr>
<td>cat. A</td>
<td>6–20 mSv/yr</td>
</tr>
<tr>
<td>cat. B</td>
<td>1–6 mSv/yr</td>
</tr>
<tr>
<td>neighborhood outside radiation areas</td>
<td></td>
</tr>
<tr>
<td>&lt; 1 mSv/yr</td>
<td>permanent residence</td>
</tr>
<tr>
<td>limit for the general public</td>
<td></td>
</tr>
<tr>
<td>for discharges from nuclear facilities</td>
<td></td>
</tr>
<tr>
<td>≤ 0.3 mSv/yr</td>
<td></td>
</tr>
</tbody>
</table>

1 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. 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).

<table>
<thead>
<tr>
<th>type of radiation and energy range</th>
<th>radiation weighting factor $w_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>photons, all energies</td>
<td>1</td>
</tr>
<tr>
<td>electrons and muons, all energies</td>
<td>1</td>
</tr>
<tr>
<td>neutrons $&lt; 10$ keV</td>
<td>5</td>
</tr>
<tr>
<td>$10$ keV–$100$ keV</td>
<td>10</td>
</tr>
<tr>
<td>$&gt; 100$ keV–$2$ MeV</td>
<td>20</td>
</tr>
<tr>
<td>$&gt; 2$ MeV–$20$ MeV</td>
<td>10</td>
</tr>
<tr>
<td>$&gt; 20$ MeV</td>
<td>5</td>
</tr>
<tr>
<td>protons, except recoil protons,</td>
<td>5</td>
</tr>
<tr>
<td>energy $&gt; 2$ MeV</td>
<td></td>
</tr>
<tr>
<td>$\alpha$ particles, fission</td>
<td>20</td>
</tr>
<tr>
<td>fragments, heavy nuclei</td>
<td></td>
</tr>
</tbody>
</table>

1 The radiation weighting factors as adopted in the United States, which are somewhat different, are given in Table 6.1 on page 94.
The following tissue weighting factors $w_T$ are almost generally accepted in all countries, see also Chaps. 2 and 6.\(^1\)

<table>
<thead>
<tr>
<th>organs or tissue</th>
<th>tissue weighting factor $w_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>gonads</td>
<td>0.20</td>
</tr>
<tr>
<td>red bone marrow</td>
<td>0.12</td>
</tr>
<tr>
<td>large intestine</td>
<td>0.12</td>
</tr>
<tr>
<td>lung</td>
<td>0.12</td>
</tr>
<tr>
<td>stomach</td>
<td>0.12</td>
</tr>
<tr>
<td>bladder</td>
<td>0.05</td>
</tr>
<tr>
<td>chest</td>
<td>0.05</td>
</tr>
<tr>
<td>liver</td>
<td>0.05</td>
</tr>
<tr>
<td>esophagus</td>
<td>0.05</td>
</tr>
<tr>
<td>thyroid gland</td>
<td>0.05</td>
</tr>
<tr>
<td>skin</td>
<td>0.01</td>
</tr>
<tr>
<td>periosteum (bone surface)</td>
<td>0.01</td>
</tr>
<tr>
<td>other organs or tissue</td>
<td>0.05</td>
</tr>
</tbody>
</table>

\(^1\) 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.

<table>
<thead>
<tr>
<th>quantity</th>
<th>symbol</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>velocity of light*</td>
<td>c</td>
<td>299 792 458</td>
<td>m/s</td>
</tr>
<tr>
<td>Planck constant</td>
<td>h</td>
<td>6.626 07 × 10(^{-34})</td>
<td>J s</td>
</tr>
<tr>
<td>electron charge magnitude</td>
<td>e</td>
<td>1.602 177 × 10(^{-19})</td>
<td>C</td>
</tr>
<tr>
<td>electron mass</td>
<td>(m_e)</td>
<td>9.109 38 × 10(^{-31})</td>
<td>kg</td>
</tr>
<tr>
<td>proton mass</td>
<td>(m_p)</td>
<td>1.672 62 × 10(^{-27})</td>
<td>kg</td>
</tr>
<tr>
<td>(\alpha)-particle mass</td>
<td>(m_\alpha)</td>
<td>6.644 661 8 × 10(^{-27})</td>
<td>kg</td>
</tr>
<tr>
<td>unified atomic mass unit</td>
<td>(m_u)</td>
<td>1.660 54 × 10(^{-27})</td>
<td>kg</td>
</tr>
<tr>
<td>electron–proton mass ratio</td>
<td>(m_e/m_p)</td>
<td>5.446 170 21 × 10(^{-4})</td>
<td></td>
</tr>
<tr>
<td>permittivity of free space*</td>
<td>(\varepsilon_0 = 1/(\mu_0 c^2))</td>
<td>8.854 187 \ldots × 10(^{-12})</td>
<td>F/m</td>
</tr>
<tr>
<td>permeability of free space*</td>
<td>(\mu_0)</td>
<td>4 π × 10(^{-7})</td>
<td>N/A(^2)</td>
</tr>
<tr>
<td>fine-structure constant</td>
<td>(\alpha = e^2/(4 \pi \varepsilon_0 h c))</td>
<td>1/137.035 999</td>
<td></td>
</tr>
<tr>
<td>classical electron radius</td>
<td>(r_e = e^2/(4 \pi \varepsilon_0 m_e c^2))</td>
<td>2.817 940 \ldots × 10(^{-15})</td>
<td>m</td>
</tr>
<tr>
<td>Compton wavelength</td>
<td>(\lambda_C = h/(m_e c))</td>
<td>2.426 310 2 \cdot 10(^{-12})</td>
<td>m</td>
</tr>
<tr>
<td>gravitational constant</td>
<td>(\gamma)</td>
<td>6.674 \times 10(^{-11})</td>
<td>m(^3)/(kg s(^2))</td>
</tr>
<tr>
<td>standard gravitational acceleration*</td>
<td>(g)</td>
<td>9.806 65</td>
<td>m/s(^2)</td>
</tr>
<tr>
<td>Avogadro constant</td>
<td>(N_A)</td>
<td>6.022 14 × 10(^{23})</td>
<td>mol(^{-1})</td>
</tr>
<tr>
<td>Boltzmann constant</td>
<td>(k)</td>
<td>1.380 65 \times 10(^{-23})</td>
<td>J/K</td>
</tr>
<tr>
<td>molar gas constant</td>
<td>(R (= N_A k))</td>
<td>8.3144</td>
<td>J/(K mol)</td>
</tr>
<tr>
<td>molar volume(^1)</td>
<td>(V_{\text{mole}})</td>
<td>22.414 \times 10(^{-3})</td>
<td>m(^3)/mol</td>
</tr>
<tr>
<td>Rydberg energy</td>
<td>(E_{\text{Ry}} = m_e c^2 \alpha^2/2)</td>
<td>13.6057</td>
<td>eV</td>
</tr>
<tr>
<td>Stefan–Boltzmann constant</td>
<td>(\sigma = \pi^2 k^4/(60 h^3 c^2))</td>
<td>5.6704 × 10(^{-8})</td>
<td>W m(^{-2}) K(^{-4})</td>
</tr>
<tr>
<td>Bohr radius</td>
<td>(a_0 = 4 \pi \varepsilon_0 h^2/(m_e c^2))</td>
<td>0.529 177 21 \times 10(^{-10})</td>
<td>m</td>
</tr>
<tr>
<td>Faraday constant</td>
<td>(F = e N_A)</td>
<td>96 485.309</td>
<td>C/mol</td>
</tr>
<tr>
<td>electron charge-to-mass ratio</td>
<td>(e/m_e)</td>
<td>1.758 820 \times 10(^{11})</td>
<td>C/kg</td>
</tr>
</tbody>
</table>

\(^1\) at standard temperature and pressure \((T = 273.15 K, \ p = 101 325 \text{ Pa})\)
# I Useful Conversions

<table>
<thead>
<tr>
<th>quantity</th>
<th>conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>force</td>
<td>1 N = 1 kg m/s²</td>
</tr>
<tr>
<td>work, energy</td>
<td>1 eV = 1.602 177 × 10⁻¹⁹ J</td>
</tr>
<tr>
<td></td>
<td>1 cal = 4.186 J</td>
</tr>
<tr>
<td></td>
<td>1 erg = 10⁻⁷ J</td>
</tr>
<tr>
<td></td>
<td>1 kWh = 3.6 × 10⁶ J</td>
</tr>
<tr>
<td>energy dose</td>
<td>1 Gy = 100 rad</td>
</tr>
<tr>
<td></td>
<td>1 rad = 10 mGy</td>
</tr>
<tr>
<td>dose equivalent</td>
<td>1 Sv = 100 rem</td>
</tr>
<tr>
<td></td>
<td>1 rem = 10 mSv</td>
</tr>
<tr>
<td>ion dose</td>
<td>1 R = 258 μC/kg</td>
</tr>
<tr>
<td></td>
<td>≈ 8.77 × 10⁻³ Gy (in air)</td>
</tr>
<tr>
<td>ion-dose rate</td>
<td>1 R/h = 7.17 × 10⁻⁸ A/kg</td>
</tr>
<tr>
<td>activity</td>
<td>1 Ci = 3.7 × 10¹⁰ Bq</td>
</tr>
<tr>
<td></td>
<td>1 Bq = 27.03 pCi</td>
</tr>
<tr>
<td>pressure</td>
<td>1 bar = 10⁵ Pa</td>
</tr>
<tr>
<td></td>
<td>1 atm = 1.013 25 × 10⁵ Pa</td>
</tr>
<tr>
<td></td>
<td>1 Torr = 1 mm Hg</td>
</tr>
<tr>
<td></td>
<td>= 1.333 224 × 10² Pa</td>
</tr>
<tr>
<td></td>
<td>1 kp/m² = 9.806 65 Pa</td>
</tr>
<tr>
<td>charge</td>
<td>1 C = 2.997 924 58 × 10⁹ esu¹</td>
</tr>
<tr>
<td>length</td>
<td>1 m = 10¹⁰ Å</td>
</tr>
<tr>
<td>temperature</td>
<td>θ [°C] = T [K] - 273.15</td>
</tr>
<tr>
<td></td>
<td>T [°Fahrenheit] = 1.80 θ [°C] + 32</td>
</tr>
<tr>
<td></td>
<td>= 1.80 T [K] - 459.67</td>
</tr>
<tr>
<td>time</td>
<td>1 d = 86 400 s</td>
</tr>
<tr>
<td></td>
<td>1 yr = 3.1536 × 10⁷ s</td>
</tr>
</tbody>
</table>

¹ esu – electrostatic unit
J List of Abbreviations

Å – angstrom (unit of length); 1 Å = 10⁻¹⁰ 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: arcus tangens): 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 βαρ, ‘weight’
barn – unit of the (total) cross section (= 10⁻²⁴ cm²)
BF₃ – 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 Européenne 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 ($e = 2.718281 \ldots$)
EC – electron capture (mostly from the K shell)
EDTA – ethylenediamine tetraacetate
erg – unit of energy (1 g cm$^2$/s$^2$); from the Greek $\epsilon\rho\gamma\omicron$, ‘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 J = 10^7 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
μC – microcoulomb
mCi – millicurie
μCi – microcurie
meV – milli electron volt
MeV – mega electron volt
mGy – milligray
μGy – microgray
mK – millikelvin
μK – microkelvin
mole – amount of material which contains 6.022 × 10^23 molecules/atoms (= Avogadro number)
MOSFET – Metal Oxide Field Effect Transistor
MOX – Mixture of Oxides
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>mrem</td>
<td>millirem</td>
</tr>
<tr>
<td>MRT</td>
<td>Microbeam Radiation Therapy</td>
</tr>
<tr>
<td>mSv</td>
<td>millisievert</td>
</tr>
<tr>
<td>μSv</td>
<td>microsievert</td>
</tr>
<tr>
<td>mV</td>
<td>millivolt</td>
</tr>
<tr>
<td>MW</td>
<td>megawatt</td>
</tr>
<tr>
<td>N</td>
<td>newton (unit of force)</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NEA</td>
<td>Nuclear Energy Agency</td>
</tr>
<tr>
<td>NIR</td>
<td>Non-Ionizing Radiation</td>
</tr>
<tr>
<td>NPL</td>
<td>National Physical Laboratory</td>
</tr>
<tr>
<td>nSv</td>
<td>nanosievert</td>
</tr>
<tr>
<td>OECD</td>
<td>Organization for Economic Cooperation and Development</td>
</tr>
<tr>
<td>Ω</td>
<td>ohm</td>
</tr>
<tr>
<td>Pa</td>
<td>pascal (unit of pressure)</td>
</tr>
<tr>
<td>PBD</td>
<td>2-(4-tert.-butylene-phenyl)-5-(4-biphenyl-1,3,4-oxadiazole)</td>
</tr>
<tr>
<td>pCi</td>
<td>picocurie</td>
</tr>
<tr>
<td>PET</td>
<td>Positron-Emission Tomography</td>
</tr>
<tr>
<td>pF</td>
<td>picofarad (10^{-12} F)</td>
</tr>
<tr>
<td>PIPS detector</td>
<td>Passive Implanted Planar Silicon detector</td>
</tr>
<tr>
<td>PM</td>
<td>photomultiplier</td>
</tr>
<tr>
<td>PMMA</td>
<td>polymethyl methacrylate</td>
</tr>
<tr>
<td>ppm</td>
<td>parts per million (10^{-6})</td>
</tr>
<tr>
<td>PTB</td>
<td>German national physical laboratory for weights and measures (Physikalisch–Technische Bundesanstalt in Braunschweig, equivalent to the British NPL)</td>
</tr>
<tr>
<td>R</td>
<td>roentgen</td>
</tr>
<tr>
<td>rad</td>
<td>radiation absorbed dose</td>
</tr>
<tr>
<td>rad</td>
<td>radian (unit of angle, the full radian is 2π)</td>
</tr>
<tr>
<td>Radar</td>
<td>Radio Detecting and Ranging</td>
</tr>
<tr>
<td>rem</td>
<td>roentgen equivalent man</td>
</tr>
<tr>
<td>RBE</td>
<td>relative biological effectiveness</td>
</tr>
<tr>
<td>RID</td>
<td>règlement international concernant le transport des marchandises dangereuses provision about the transport of dangerous goods</td>
</tr>
<tr>
<td>RNA</td>
<td>ribonucleic acid</td>
</tr>
<tr>
<td>RTG</td>
<td>Radioisotope Thermoelectric Generator</td>
</tr>
<tr>
<td>SAR</td>
<td>specific absorption rate</td>
</tr>
</tbody>
</table>
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),

Ws – watt second (unit of energy)
K List of Elements*

1 H hydrogen (Greek: υδωρ, hydor, water + γεινομαι, geinomai, to engender; Latin: hydrogenium);
   D = 2H deuterium (Greek: δευτερος, deuteros, second) and T = 3H 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
   resp. www.webelements.com/
   or http://elements.vanderkrogt.net/elem/
40 Zr zirconium (Persian: zargûn, gold color)
41 Nb niobium (Greek: μολυβδος, molyblos, lead ore)
42 Mo molybdenum (Greek: μολυβδος, molyblos, 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)
47 Aг 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, cosmetic powder)
52 Te tellurium (Latin: tellus, earth, ground)
53 I iodine (Greek: ιωειδης, ioeides, violet color)
54 Xe xenon (Greek: ξηνος, xenos, strange)
55 Cs cesium (Latin: caesius = bluish gray)
56 Ba barium (Greek: βαρυς, barys, heavy)
57 La lanthanum (Greek: λανθανω, lanthano, to lie hidden)
58 Ce cerium (Ceres, asteroid discovered in 1801)
59 Pr praseodymium (Greek: πρασιως + 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 erbia (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 = Köbenhavn, Copenhagen)
73 Ta tantalum (Greek: Tανταλος, 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, 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, hydrargyros, 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)
91 Pa protactinium (Greek: πρωτος + actinium, first element after actinium in the uranium–actinium decay series)
92 U uranium (named after the planet Uranus)
93 Np neptunium (named after the planet Neptune)
94 Pu plutonium (named after the dwarf planet Pluto (Πλούτων, Plouton), the Greek god of the underworld)
95 Am americium (Latin: America)
96 Cm curium (named after Marie Curie)
97 Bk berkelium (Berkeley, town in California)
98 Cf californium (California, state of the USA)
99 Es einsteinium (named after Albert Einstein)
100 Fm fermium (named after Enrico Fermi)
101 Md mendelevium (named after Dmitri I. Mendeleyev)
102 No nobelium (named after Alfred Nobel)
103 Lr lawrencium (named after Ernest O. Lawrence)
104 Rf rutherfordium (named after Ernest Rutherford)
105 Db dubnium (named after Dubna, a town in the Moscow region)
106 Sg seaborgium (named after Glenn T. Seaborg)
107 Bh bohrium (named after Niels Bohr)
108 Hs hassium (named after the German state Hassia, Hessen)
109 Mt meitnerium (named after Lise Meitner)
110 Ds darmstadtium (named after Darmstadt, a town in Germany)
111 Rg roentgenium (named after Wilhelm Conrad Röntgen)
112 Cn copernicium (named after Nicolaus Copernicus)
113 †
114 †
115 †
116 †
118 †

† 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 = annus, year)

Figure L.2
Thorium (\(^{232}\text{Th}\)) decay chain
(a = annus, year)
Figure L.3
Actinium ($^{235}\text{U}$) decay chain
(a = annus, year)

Figure L.4
Neptunium ($^{237}\text{Np}$) decay chain
(a = annus, year)
## M List of Isotopes Frequently Used in Nuclear Medicine and Radiology

<table>
<thead>
<tr>
<th>isotope</th>
<th>half-life</th>
<th>decay</th>
<th>main energy</th>
<th>application</th>
</tr>
</thead>
<tbody>
<tr>
<td>protons</td>
<td>stable</td>
<td></td>
<td>≈ 200 MeV</td>
<td>particle therapy</td>
</tr>
<tr>
<td>$^3$H</td>
<td>12.3 yrs</td>
<td>$\beta^-$, no $\gamma$</td>
<td>0.02 MeV</td>
<td>total body water content determination</td>
</tr>
<tr>
<td>$^{11}$B</td>
<td>stable</td>
<td></td>
<td></td>
<td>melanoma and brain tumor treatment</td>
</tr>
<tr>
<td>$^{11}$C</td>
<td>20.4 min</td>
<td>$\beta^+$, no $\gamma$</td>
<td>1.0 MeV</td>
<td>Positron-Emission Tomography; PET scans</td>
</tr>
<tr>
<td>$^{12}$C</td>
<td>stable</td>
<td></td>
<td>≈ 300 MeV per nucleon</td>
<td>particle therapy</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>5730 yrs</td>
<td>$\beta^-$, no $\gamma$</td>
<td>0.2 MeV</td>
<td>e.g. pancreatic studies</td>
</tr>
<tr>
<td>$^{13}$N</td>
<td>10 min</td>
<td>$\beta^+$, no $\gamma$</td>
<td>1.2 MeV</td>
<td>Positron-Emission Tomography; PET scans</td>
</tr>
<tr>
<td>$^{15}$O</td>
<td>2 min</td>
<td>$\beta^+$, no $\gamma$</td>
<td>1.7 MeV</td>
<td>Positron-Emission Tomography; PET scans</td>
</tr>
<tr>
<td>$^{18}$F</td>
<td>110 min</td>
<td>$\beta^+$, no $\gamma$</td>
<td>0.6 MeV</td>
<td>Positron-Emission Tomography; PET scans</td>
</tr>
<tr>
<td>$^{22}$Na</td>
<td>2.6 yrs</td>
<td>$\beta^+$</td>
<td>0.5 MeV ...</td>
<td>electrolyte studies</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\gamma$</td>
<td>1275 keV</td>
<td></td>
</tr>
<tr>
<td>$^{24}$Na</td>
<td>15 h</td>
<td>$\beta^-$</td>
<td>1.4 MeV ...</td>
<td>studies of electrolytes within the body</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\gamma$</td>
<td>2754 keV ...</td>
<td></td>
</tr>
<tr>
<td>$^{32}$P</td>
<td>14.3 d</td>
<td>$\beta^-$, no $\gamma$</td>
<td>1.7 MeV</td>
<td>treatment against excess of red blood cells</td>
</tr>
<tr>
<td>$^{42}$K</td>
<td>12.4 h</td>
<td>$\beta^-$</td>
<td>3.5 MeV ...</td>
<td>for measurement of coronary blood flow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\gamma$</td>
<td>1525 keV ...</td>
<td></td>
</tr>
<tr>
<td>$^{47}$Ca</td>
<td>4.5 d</td>
<td>$\beta^-$</td>
<td>0.7 MeV ...</td>
<td>bone metabolism</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\gamma$</td>
<td>1297 keV ...</td>
<td></td>
</tr>
<tr>
<td>$^{51}$Cr</td>
<td>27.7 d</td>
<td>$\gamma$</td>
<td>320 keV</td>
<td>labeling of red blood cells</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{59}$Fe</td>
<td>44.5 d</td>
<td>$\beta^-$</td>
<td>0.5 MeV ...</td>
<td>metabolism in the spleen</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\gamma$</td>
<td>1099 keV ...</td>
<td></td>
</tr>
<tr>
<td>$^{57}$Co</td>
<td>272 d</td>
<td>$\gamma$</td>
<td>122 keV ...</td>
<td>marker to estimate organ size</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isotope</td>
<td>Half-Life</td>
<td>Decay</td>
<td>Main Energy</td>
<td>Application</td>
</tr>
<tr>
<td>---------</td>
<td>-----------</td>
<td>-------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>$^{58}$Co</td>
<td>71 d</td>
<td>$\beta^+$</td>
<td>0.5 MeV ... 811 keV</td>
<td>gastrointestinal absorption</td>
</tr>
<tr>
<td>$^{60m}$Co</td>
<td>10.5 min</td>
<td>$\gamma$</td>
<td>59 keV</td>
<td>external beam radiotherapy</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>5.3 yrs</td>
<td>$\beta^-$</td>
<td>0.3 MeV ... 1173 keV</td>
<td>tumor treatment</td>
</tr>
<tr>
<td>$^{62}$Cu</td>
<td>9.7 min</td>
<td>$\beta^+$</td>
<td>2.9 MeV ... 1346 keV</td>
<td>positron-emitting radionuclide for PET</td>
</tr>
<tr>
<td>$^{64}$Cu</td>
<td>12.7 h</td>
<td>$\beta^-$</td>
<td>0.6 MeV ... 185 keV</td>
<td>study of genetic of diseases</td>
</tr>
<tr>
<td>$^{64}$Ga</td>
<td>2.6 min</td>
<td>$\beta^+$</td>
<td>2.9 MeV ... 992 keV</td>
<td>treatment of pulmonary diseases</td>
</tr>
<tr>
<td>$^{67}$Ga</td>
<td>78.3 h</td>
<td>$\gamma$</td>
<td>93 keV ...  (\gamma)</td>
<td>tumor imaging</td>
</tr>
<tr>
<td>$^{68}$Ga</td>
<td>67.6 min</td>
<td>$\beta^+$</td>
<td>1.9 MeV ... 1077 keV</td>
<td>study thrombosis and atherosclerosis</td>
</tr>
<tr>
<td>$^{68}$Ge</td>
<td>271 d</td>
<td>no $\beta^+$, no $\gamma$, EC</td>
<td>PET imaging</td>
<td></td>
</tr>
<tr>
<td>$^{72}$As</td>
<td>26 h</td>
<td>$\beta^+$</td>
<td>2.5 MeV ... 834 keV</td>
<td>planar imaging, SPECT, or PET</td>
</tr>
<tr>
<td>$^{75}$Se</td>
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<td>Application</td>
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**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),  
### Critical Organs for Various Radioisotopes

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</table>
Abbreviations

sf – spontaneous fission
EC – electron capture

References:

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Safety series no. 47. Recommendations (IAEA, Vienna, 1978);
Nuclear Instruments and Methods, Vol. 161, issue 1, p. 172 (1979)
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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.
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.
O  Simplified Table of Isotopes and Periodic Table of Elements

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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.
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.
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 $^{22}$Na

Characteristic X rays of $^{55}$Mn:
- $K_{\alpha} = 5.9$ keV
- $K_{\beta} = 6.5$ keV

Figure P.2
Decay-level scheme of $^{55}$Fe
Conversion electrons:
K(γ₁) = 0.115 MeV  L(γ₁) = 0.121 MeV
K(γ₂) = 0.0073 MeV  L(γ₂) = 0.0136 MeV
K(γ₃) = 0.1294 MeV  L(γ₃) = 0.1341 MeV

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

Figure P.4
Decay-level scheme of $^{60}$Co
Figure P.5
Decay-level scheme of $^{90}\text{Sr}$

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

\[ K(\gamma) = 0.0625 \text{ MeV} \]
\[ L(\gamma) = 0.0842 \text{ MeV} \]
\[ M(\gamma) = 0.0873 \text{ MeV} \]

Conversion X rays:

\[ K_{\alpha} \text{ X-ray: 0.022 MeV} \]
\[ K_{\beta} \text{ X-ray: 0.025 MeV} \]
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:

$K(\gamma_1)$ 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.

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 infinitesimal 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

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

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 $v = \frac{dx}{dt}$ 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:

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

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

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

one gets

$$\frac{dx(t)}{dt} = b + 2 \, c \, t. \quad (Q.4)$$
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 $bt$ is equal to $b$, and the slope 
of a parabola $ct^2$ is obtained to be $2 ct$).\(^1\)

In general, a power-law relation is differentiated as

\[
\frac{d}{dt} t^n = n t^{n-1} . \tag{Q.5}
\]

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 $v(t) = at$, 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 $v(t) = at$ 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 $v_1 = at_1$ divided by 2,

\[
\frac{t_1 a t_1}{2} = \frac{1}{2} a t_1^2 . \tag{Q.6}
\]

For this operation one uses as shorthand the integral over the function 
v = $at$ in the limits from $t = 0$ to $t = t_1$:\(^2\)

\[
\int_0^{t_1} a t \, dt = \left. \frac{1}{2} a t^2 \right|_0^{t_1} = \frac{1}{2} a t_1^2 . \tag{Q.7}
\]

The general rule for integrating a polynomial reads:

\[
\int_0^{t_1} t^n \, dt = \left. \frac{t^{n+1}}{n+1} \right|_0^{t_1} = \frac{t_1^{n+1}}{n+1} . \tag{Q.8}
\]

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):

\[
\int t^n \, dt = \frac{t^{n+1}}{n+1} + \text{const} . \tag{Q.9}
\]

\[
\frac{1}{2} c \frac{(t+c \Delta t)^2 - c (t-c \Delta t)^2}{\Delta t} = \frac{c (t^2 + t \Delta t + \frac{\Delta t^2}{2}) - c (t^2 - t \Delta t + \frac{\Delta t^2}{2})}{\Delta t} = \frac{2 c t \Delta t}{\Delta t} =
\]

\[
\frac{2 c t}{\Delta t} \tag{Q.10}
\]

\(^2\) In general, the integral over a linear function between two arbitrary limits 
t_1 and $t_2$ is worked out to be:

\[
\int_{t_1}^{t_2} a t \, dt = \left. \frac{1}{2} a t^2 \right|_{t_1}^{t_2} = \frac{1}{2} a t_2^2 - \frac{1}{2} a t_1^2 = \frac{1}{2} a \left( t_2^2 - t_1^2 \right) . \tag{Q.11}
\]
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:

\[
\Delta N \sim -N \Delta t . \quad (Q.10)
\]

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

\[
dN \sim -N \, dt . \quad (Q.11)
\]

The introduction of a constant of proportionality leads to the identity

\[
dN = -\lambda \, N \, dt , \quad (Q.12)
\]

where \( \lambda \) is the decay constant. Such a relation – one of the most basic differential equations – is solved by the so-called exponential function

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

The number \( e \), first introduced by Leonhard Euler, has the numerical value of \( e = 2.71828 \ldots \). 

\( N_0 \) 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,

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

---

\[
^3 \frac{dN}{N} = -\lambda \, dt \Rightarrow \int \frac{dN}{N} = -\int \lambda \, dt \Rightarrow \ln N = -\lambda t + \text{const} \quad (\text{see also Eq. (Q.25)}), \quad e^{\ln N} = N = e^{-\lambda t + \text{const}} = e^{-\lambda t} e^{\text{const}} ; \quad \text{boundary condition} \quad N(t = 0) = e^{\text{const}} = N_0 \Rightarrow N = N_0 e^{-\lambda t} .
\]
It is the only function with this astonishing feature. If there is a parameter $\alpha$ as factor in the exponent, one has
\[
\frac{d}{dt} e^{\alpha t} = \alpha e^{\alpha t}.
\] (Q.15)

In the same way the integration of the function $e^t$ retrieves the exponential function,
\[
\int e^t \, dt = e^t + \text{const} \, ,
\] (Q.16)

and correspondingly
\[
\int e^{\alpha t} \, dt = \frac{1}{\alpha} e^{\alpha t} + \text{const} \, .
\] (Q.17)

The known rules for powers also apply to exponentials, e.g.
\[
e^{\alpha} e^{\beta} = e^{\alpha + \beta} \, .
\] (Q.18)

**Q.3 Natural Logarithm**

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
\[
e^{y} = x
\] (Q.19)

is exactly fulfilled, if
\[
y = \ln x \, .
\] (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.\(^4\)

\(^4\) 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.
\[ \ln(x \cdot y) = \ln x + \ln y , \]
\[ \ln \frac{x}{y} = \ln x - \ln y , \]
\[ \ln x^n = n \ln x . \]

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

Since the integration is the inverse operation to differentiation, one has
\[ \int \frac{1}{x} \, dx = \ln x + \text{const} . \]

With these rules also the radioactive decay law can now be understood: From
\[ N = N_0 e^{-\lambda t} \]
one obtains by differentiating
\[ \frac{dN}{dt} = -\lambda N_0 e^{-\lambda t} = -\lambda N , \]
which can be rewritten as
\[ dN = -\lambda N \, dt \]
(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).\(^6\)

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:

\(^5\) \( e^x = x ; \ y = \ln x ; \ \frac{d \ln x}{dx} = \frac{dy}{dx} = \frac{1}{x} = \frac{1}{e^y} = \frac{1}{\ln e} = \frac{1}{x} \)

\(^6\) 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 \( \lg 10 = 1 \).
and
\[ \ln N = \ln N_0 - \lambda t \] (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
\[ y = x^n \] (Q.31)
leads to
\[ \ln y = n \ln x \], (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
Further Reading

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www.mpanrw.de/start.html

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www.oxfordtechnologies.co.uk

PTW–Freiburg
Physikalisch–Technische Werkstätten Dr. Pychlau GmbH
Lörracher Strasse 7
79115 Freiburg
Germany
www.ptw.de

QSA Global GmbH
Gieselweg 1
38110 Braunschweig
Germany
QSA Global Inc.
40 North Avenue
Burlington, MA 01803
USA
Sales offices also in France and Honk Kong
www.qsa-global.de
www.isottrak.de

RadiologyInfo™
www.radiologyinfo.org
nmap@acr.org
mamm-accred@acr.org

Radon Lab
Forskningsveien 3 B
0373 Oslo
Norway
www.radonlab.net/tracketch.htm

RADOS Technology GmbH
Ruhrstrasse 49
D-22761 Hamburg
Germany
World Headquarters
Bishop Ranch 8
3000 Executive Parkway Suite 220
San Ramon, CA 94583
USA

Many international representatives (21) to be found under:
www.mirion.com/index.php?p=locations#noram

S.E.A. GmbH
(Strahlenschutz-Entwicklungs- und Ausrüstungs-Gesellschaft)
Ortsdamm 139
48249 Dülmen
Germany
www.sea-duelmen.de

Siemens Healthcare
Wittelsbacherplatz 2
80333 München
Germany
Representatives in 35 countries
www.medical.siemens.com/
Strahlenzentrum of the Justus-Liebig University Giessen
Leihgesterner Weg 217
35392 Giessen
Germany
www.strz.uni-giessen.de/

Synchrotron Radiation Angiography (St. Fiedler)
Canadian Light Source Inc.
University of Saskatchewan
101 Perimeter Road
Saskatoon, SK.
Canada, S7N 0X4
www.lightsource.ca/
www.lightsource.ca/bioimaging/Saskatoon_2004_sf.pdf

Terra Universal, Inc.
800 S. Raymond Avenue,
Fullerton, CA 92831
USA
www.terrauniversal.com
Many international representatives (21) to be found under:
www.terrauniversal.com/international/localreps.shtml

Thermo Eberline ESM
Frauenauracher Strasse 96
91056 Erlangen
Germany
www.esm-online.de/

Thermo Fisher Scientific Inc.
81 Wyman Street
Waltham, MA 02454
USA
www.thermo.com/
Many international representatives (209) to be found under:
www.thermo.com/com/cda/article/general/1,,882,00.html

US Department of Energy
Office of Civilian Radioactive Waste Management
Yucca Mountain Project
1551 Hillshire Drive
Las Vegas, NV 89134
USA
www.ocrwm.doe.gov/contact/index.shtml
www.ocrwm.doe.gov/factsheets/doeymp0010.shtml
VacuTec Meßtechnik GmbH
Dornblüthstrasse 14
D-01277 Dresden
Germany
www.e-meditec.de/firm05/vacutec_messtechnik_4508.htm

Wikipedia
http://commons.wikimedia.org/wiki/Image:Coolidge_xray_tube.jpg

This list has been checked early in 2009. Many companies occasionally change their name and can no longer be found easily. The ‘Supplier Name Change’ list helps to locate the companies with their new names. This list can be found under
www.purchasing.upenn.edu/buyinfo/suppliers/name_changes.php.
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