Chapter 3

Elements, Isotopes and Radioactivity
### 3.1 PERIODIC TABLE OF ELEMENTS: A GEOCHEMICAL CLASSIFICATION (Figure 3.1)

<table>
<thead>
<tr>
<th>Period</th>
<th>Element</th>
<th>Geochemical Classification</th>
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<tbody>
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<td>H</td>
<td>Atmosphere, concentrated in the atmosphere</td>
</tr>
<tr>
<td>2</td>
<td>He</td>
<td>Crustophile, concentrated in the crust</td>
</tr>
<tr>
<td>3</td>
<td>Li</td>
<td>Lithophile, occurring in mantle silicates</td>
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<tr>
<td>4</td>
<td>Be</td>
<td>Siderophile, soluble in liquid iron and probable core constituent</td>
</tr>
<tr>
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<td>B</td>
<td>Chalcophile, forms sulphide in the absence of oxygen</td>
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<tr>
<td>6</td>
<td>C</td>
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**Figure 3.1**  A geochemical classification of the elements.
### 3.2 PERIODIC TABLE OF ELEMENTS: A BIOLOGICAL CLASSIFICATION (Figure 3.2)

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**Figure 3.2** A biological classification of the elements.
### 3.3 ISOTOPES OF THE NATURALLY OCCURRING ELEMENTS

#### Table 3.1 Isotopic Abundances and Mean Atomic Weights

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<th>Element</th>
<th>Symbol (mean atomic wt., in units of ( u = 1.66053878 \times 10^{-27} \text{ kg} ))</th>
<th>Isotopic Masses, with Abundances in Atomic % in Parentheses</th>
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<td>He (4.00260)</td>
<td>3 (0.00013), 4 (99.9987)</td>
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<td>Li (6.940)</td>
<td>6 (7.59), 7 (92.41)</td>
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<td>Beryllium</td>
<td>Be (9.01218)</td>
<td>9 (100), 10(^{a}) (atmospheric trace from cosmic ray bombardment)</td>
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<td>10 (19.9), 11 (80.1)</td>
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<td>6</td>
<td>Carbon</td>
<td>C (12.0107)</td>
<td>12 (98.93), 13 (1.07), 14(^{a}) (1.6 \times 10^{-10} in atmosphere)</td>
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(Continued)
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<th>Atomic No.</th>
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<td>Bromine</td>
<td>Br (79.904)</td>
<td>79 (50.69), 81 (49.31)</td>
</tr>
<tr>
<td>36</td>
<td>Krypton</td>
<td>Kr (83.798)</td>
<td>78 (0.35), 80 (2.29), 82 (11.59), 83 (11.50), 84 (56.99), 86 (17.28)</td>
</tr>
<tr>
<td>37</td>
<td>Rubidium</td>
<td>Rb (85.4678)</td>
<td>85 (72.165), 87(^a) (27.835)</td>
</tr>
<tr>
<td>38</td>
<td>Strontium</td>
<td>Sr (87.62)</td>
<td>84 (0.56), 86 (9.86), 87 (7.00), 88 (82.58)</td>
</tr>
</tbody>
</table>

(Continued)
<table>
<thead>
<tr>
<th>Atomic No.</th>
<th>Element</th>
<th>Symbol (mean atomic wt., in units of $\mu = 1.66053878 \times 10^{-27}$ kg)</th>
<th>Isotopic Masses, with Abundances in Atomic % in Parentheses</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>Yttrium</td>
<td>Y (88.90585)</td>
<td>89 (100)</td>
</tr>
<tr>
<td>40</td>
<td>Zirconium</td>
<td>Zr (91.224)</td>
<td>90 (51.45), 91 (11.22), 92 (17.15), 94 (17.38), 96$^b$ (2.80)</td>
</tr>
<tr>
<td>41</td>
<td>Niobium</td>
<td>Nb (92.90638)</td>
<td>93 (100)</td>
</tr>
<tr>
<td>42</td>
<td>Molybdenum</td>
<td>Mo (95.96)</td>
<td>92 (14.77), 94 (9.23), 95 (15.90), 96 (16.68), 97 (9.56), 98 (24.19), 100$^a$ (9.67)</td>
</tr>
<tr>
<td>43</td>
<td>Technetium</td>
<td>Tc</td>
<td>No naturally occurring isotope</td>
</tr>
<tr>
<td>44</td>
<td>Ruthenium</td>
<td>Ru (101.07)</td>
<td>96 (5.44), 98 (1.87), 99 (12.76), 100 (12.60), 101 (17.06), 102 (31.55), 104 (18.62)</td>
</tr>
<tr>
<td>45</td>
<td>Rhodium</td>
<td>Rh (102.90550)</td>
<td>103 (100)</td>
</tr>
<tr>
<td>46</td>
<td>Palladium</td>
<td>Pd (106.42)</td>
<td>102 (1.02), 104 (11.14), 105 (22.33), 106 (27.33), 108 (26.46), 110 (11.72)</td>
</tr>
<tr>
<td>47</td>
<td>Silver</td>
<td>Ag (106.8682)</td>
<td>107 (51.839), 109 (48.161)</td>
</tr>
<tr>
<td>48</td>
<td>Cadmium</td>
<td>Cd (112.411)</td>
<td>106 (1.25), 108 (0.89), 110 (12.49), 111 (12.80), 112 (24.13), 113$^b$ (12.22), 114$^b$ (28.72), 116$^b$ (7.49)</td>
</tr>
<tr>
<td>49</td>
<td>Indium</td>
<td>In (114.818)</td>
<td>113 (4.29), 115$^b$ (95.71)</td>
</tr>
<tr>
<td>50</td>
<td>Tin</td>
<td>Sn (118.71)</td>
<td>112 (0.97), 114 (0.66), 115 (0.34), 116 (14.54), 117 (7.68), 118 (24.22), 119 (8.59), 120 (32.58), 122 (4.63), 124 (5.79)</td>
</tr>
<tr>
<td>51</td>
<td>Antimony</td>
<td>Sb (121.60)</td>
<td>121 (57.21), 123 (47.79)</td>
</tr>
<tr>
<td>52</td>
<td>Tellurium</td>
<td>Te (127.60)</td>
<td>120 (0.09), 122 (2.55), 123 (0.89), 124 (4.74), 125 (7.07), 126 (18.84), 128$^b$ (31.74), 130$^b$ (30.08)</td>
</tr>
<tr>
<td>53</td>
<td>Iodine</td>
<td>I (126.90448)</td>
<td>127 (100)</td>
</tr>
<tr>
<td>54</td>
<td>Xenon</td>
<td>Xe (131.293)</td>
<td>124 (0.095), 126 (0.089), 128 (1.910), 129 (26.401), 130 (4.071), 131 (21.232), 132 (26.909), 134 (10.436), 136$^b$ (8.857)</td>
</tr>
</tbody>
</table>

(Continued)
### TABLE 3.1 (Continued) ISOTOPIC ABUNDANCES AND MEAN ATOMIC WEIGHTS

<table>
<thead>
<tr>
<th>Atomic No.</th>
<th>Element</th>
<th>Symbol (mean atomic wt., in units of $u = 1.66053878 \times 10^{-27} \text{ kg}$)</th>
<th>Isotopic Masses, with Abundances in Atomic % in Parentheses</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>Caesium</td>
<td>Cs (132.90552)</td>
<td>133 (100)</td>
</tr>
<tr>
<td>56</td>
<td>Barium</td>
<td>Ba (137.327)</td>
<td>130b (0.106), 132 (0.101), 134 (2.417), 135 (6.592), 136 (7.854), 137 (11.232), 138 (71.698)</td>
</tr>
<tr>
<td>57</td>
<td>Lanthanum</td>
<td>La (138.90547)</td>
<td>138b (0.090), 139 (99.910)</td>
</tr>
<tr>
<td>58</td>
<td>Cerium</td>
<td>Ce (140.116)</td>
<td>136 (0.190), 138 (0.251), 140 (88.450), 142 (11.114)</td>
</tr>
<tr>
<td>59</td>
<td>Praseodymium</td>
<td>Pr (140.90765)</td>
<td>141 (100)</td>
</tr>
<tr>
<td>60</td>
<td>Neodymium</td>
<td>Nd (144.242)</td>
<td>142 (27.2), 143 (1.2), 144a (23.8), 145 (8.23), 146 (17.2), 148 (5.72), 150b (5.60)</td>
</tr>
<tr>
<td>61</td>
<td>Promethium</td>
<td>Pm</td>
<td>No naturally occurring isotope</td>
</tr>
<tr>
<td>62</td>
<td>Samarium</td>
<td>Sm (150.36)</td>
<td>144 (3.07), 146a (trace), 147a (14.99), 148b (11.24), 149 (13.82), 150 (7.38), 152 (26.75), 154 (22.75)</td>
</tr>
<tr>
<td>63</td>
<td>Europium</td>
<td>Eu (151.964)</td>
<td>151b (47.81), 153 (52.19)</td>
</tr>
<tr>
<td>64</td>
<td>Gadolinium</td>
<td>Gd (157.25)</td>
<td>152a (0.20), 154 (2.18), 155 (14.80), 156 (20.47), 157 (15.65), 158 (24.84), 160 (21.86)</td>
</tr>
<tr>
<td>65</td>
<td>Terbium</td>
<td>Tb (158.92535)</td>
<td>159 (100)</td>
</tr>
<tr>
<td>66</td>
<td>Dysprosium</td>
<td>Dy (162.500)</td>
<td>156 (0.056), 158 (0.095), 160 (2.329), 161 (18.889), 162 (25.475), 163 (24.896), 164 (28.260)</td>
</tr>
<tr>
<td>67</td>
<td>Holmium</td>
<td>Ho (164.93032)</td>
<td>165 (100)</td>
</tr>
<tr>
<td>68</td>
<td>Erbium</td>
<td>Er (167.259)</td>
<td>162 (0.139), 164 (1.601), 166 (33.503), 167 (22.869), 168 (26.978), 170 (14.910)</td>
</tr>
<tr>
<td>69</td>
<td>Thulium</td>
<td>Tm (168.9342)</td>
<td>169 (100)</td>
</tr>
<tr>
<td>70</td>
<td>Ytterbium</td>
<td>Yb (173.04)</td>
<td>168 (0.13), 170 (3.04), 171 (14.28), 172 (21.83), 173 (16.13), 174 (31.83), 176 (12.76)</td>
</tr>
<tr>
<td>71</td>
<td>Lutetium</td>
<td>Lu (174.967)</td>
<td>175 (97.41), 176a (2.59)</td>
</tr>
<tr>
<td>72</td>
<td>Hafnium</td>
<td>Hf (178.49)</td>
<td>174b (0.162), 176 (5.26), 177 (18.60), 178 (27.28), 179 (13.63), 180 (35.08)</td>
</tr>
</tbody>
</table>

(Continued)
TABLE 3.1 (Continued)  ISOTOPIC ABUNDANCES AND MEAN ATOMIC WEIGHTS

<table>
<thead>
<tr>
<th>Atomic No.</th>
<th>Element</th>
<th>Symbol (mean atomic wt., in units of $u = 1.66053878 \times 10^{-27}$ kg)</th>
<th>Isotopic Masses, with Abundances in Atomic % in Parentheses</th>
</tr>
</thead>
<tbody>
<tr>
<td>73</td>
<td>Tantalum</td>
<td>Ta (180.9479)</td>
<td>180 (0.012), 181 (99.988)</td>
</tr>
<tr>
<td>74</td>
<td>Tungsten</td>
<td>W (183.84)</td>
<td>180$^a$ (0.12), 182 (26.55), 183 (14.31), 184 (30.64), 186 (28.45)</td>
</tr>
<tr>
<td>75</td>
<td>Rhenium</td>
<td>Re (186.207)</td>
<td>185 (37.40), 187$^a$ (62.60)</td>
</tr>
<tr>
<td>76</td>
<td>Osmium</td>
<td>Os (190.23)</td>
<td>184 (0.02), 186$^b$ (1.59), 187 (1.96), 188 (13.24), 189 (16.15), 190 (26.26), 192 (40.78)</td>
</tr>
<tr>
<td>77</td>
<td>Iridium</td>
<td>Ir (192.217)</td>
<td>191 (37.3), 193 (62.7)</td>
</tr>
<tr>
<td>78</td>
<td>Platinum</td>
<td>Pt (195.089)</td>
<td>190$^a$ (0.014), 192 (0.782), 194 (32.967), 195 (33.832), 196 (25.242), 198 (7.163)</td>
</tr>
<tr>
<td>79</td>
<td>Gold</td>
<td>Au (196.96659)</td>
<td>197 (100)</td>
</tr>
<tr>
<td>80</td>
<td>Mercury</td>
<td>Hg (200.592)</td>
<td>196 (0.15), 198 (9.97), 199 (16.87), 200 (23.10), 201 (13.18), 202 (29.86), 204 (6.87)</td>
</tr>
<tr>
<td>81</td>
<td>Thallium</td>
<td>Tl (204.3833)</td>
<td>203 (29.52), 205 (70.48)</td>
</tr>
<tr>
<td>82</td>
<td>Lead</td>
<td>Pb (207.21) (variable)</td>
<td>204$^a$ (1.347), 206 (25.03), 207 (21.25), 208 (52.37) (averages in marine sediments)</td>
</tr>
<tr>
<td>83</td>
<td>Bismuth</td>
<td>Bi (208.9804)</td>
<td>209$^b$ (100)</td>
</tr>
<tr>
<td>84</td>
<td>Polonium</td>
<td>Po</td>
<td>Intermediate daughters in uranium and thorium decay series</td>
</tr>
<tr>
<td>85</td>
<td>Astatine</td>
<td>At</td>
<td></td>
</tr>
<tr>
<td>86</td>
<td>Radon</td>
<td>Rn</td>
<td></td>
</tr>
<tr>
<td>87</td>
<td>Francium</td>
<td>Fr</td>
<td></td>
</tr>
<tr>
<td>88</td>
<td>Radium</td>
<td>Ra</td>
<td></td>
</tr>
<tr>
<td>89</td>
<td>Actinium</td>
<td>Ac</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>Thorium</td>
<td>Th (232.0381)</td>
<td>232$^a$ (100)</td>
</tr>
<tr>
<td>91</td>
<td>Protactinium</td>
<td>Pa</td>
<td>Intermediate daughter in uranium decay</td>
</tr>
<tr>
<td>92</td>
<td>Uranium</td>
<td>U (238.0289)</td>
<td>234$^a$ (0.0055), 235$^a$ (0.7200), 238$^a$ (99.2745)</td>
</tr>
</tbody>
</table>

$^a$ Radioactive isotopes.

$^b$ Isotopes with half-lives exceeding the age of the universe.
3.4 NATURALLY OCCURRING LONG-LIVED RADIOACTIVE ISOTOPES

This list recognises half-lives exceeding the age of the universe for isotopes that have generally been regarded as stable. The possibility that $\beta$ decay rates are affected by neutrino flux is under consideration. It is not clear whether any of the following numbers are seriously affected.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>% of Element</th>
<th>Decay Mechanism</th>
<th>Half-Life (years)</th>
<th>Decay Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}$K</td>
<td>0.01167</td>
<td>89.28% $\beta$ 10.72% K 0.001% $\beta^+$</td>
<td>$1.248 \times 10^9$</td>
<td>$^{40}$Ca $^{40}$Ar $^{40}$Ar</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>0.19</td>
<td>2$\beta$</td>
<td>$4 \times 10^{19}$</td>
<td>$^{48}$Ti</td>
</tr>
<tr>
<td>$^{50}$V</td>
<td>0.25</td>
<td>$\beta$</td>
<td>$1.4 \times 10^{17}$</td>
<td>$^{50}$Cr</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>7.83</td>
<td>2$\beta$</td>
<td>$1.8 \times 10^{21}$</td>
<td>$^{76}$Se</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>8.73</td>
<td>2$\beta$</td>
<td>$9.7 \times 10^{19}$</td>
<td>$^{82}$Kr</td>
</tr>
<tr>
<td>$^{87}$Rb</td>
<td>27.835</td>
<td>$\beta$</td>
<td>$4.92 \times 10^{10}$</td>
<td>$^{87}$Sr</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>2.80</td>
<td>2$\beta$</td>
<td>$2 \times 10^{19}$</td>
<td>$^{96}$Mo</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>9.67</td>
<td>2$\beta$</td>
<td>$8.5 \times 10^{18}$</td>
<td>$^{100}$Ru</td>
</tr>
<tr>
<td>$^{113}$Cd</td>
<td>12.22</td>
<td>$\beta$</td>
<td>$8.04 \times 10^{15}$</td>
<td>$^{113}$I</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>7.49</td>
<td>2$\beta$</td>
<td>$2.8 \times 10^{19}$</td>
<td>$^{116}$Sn</td>
</tr>
<tr>
<td>$^{118}$In</td>
<td>95.71</td>
<td>$\beta$</td>
<td>$4.4 \times 10^{14}$</td>
<td>$^{118}$Sn</td>
</tr>
<tr>
<td>$^{128}$Te</td>
<td>31.74</td>
<td>2$\beta$</td>
<td>$2.2 \times 10^{24}$</td>
<td>$^{128}$Xe</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>30.08</td>
<td>2$\beta$</td>
<td>$7.9 \times 10^{20}$</td>
<td>$^{130}$Xe</td>
</tr>
<tr>
<td>$^{130}$Ba</td>
<td>0.106</td>
<td>2K</td>
<td>$\sim 10^{21}$</td>
<td>$^{130}$Xe</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>8.857</td>
<td>2$\beta$</td>
<td>$2.38 \times 10^{21}$</td>
<td>$^{136}$Ba</td>
</tr>
<tr>
<td>$^{138}$La</td>
<td>0.090</td>
<td>33.6% $\beta$ 66.4% $\beta^+$</td>
<td>$1.02 \times 10^{11}$</td>
<td>$^{138}$Ce $^{138}$Ba</td>
</tr>
<tr>
<td>$^{142}$Ce</td>
<td>11.05</td>
<td>$\alpha$</td>
<td>$5.0 \times 10^{15}$</td>
<td>$^{138}$Ba</td>
</tr>
<tr>
<td>$^{144}$Nd</td>
<td>23.8</td>
<td>$\alpha$</td>
<td>$2.3 \times 10^{15}$</td>
<td>$^{140}$Ce</td>
</tr>
<tr>
<td>$^{146}$Sm</td>
<td>trace</td>
<td>$\alpha$</td>
<td>$6.8 \times 10^{7}$</td>
<td>$^{142}$Nd</td>
</tr>
<tr>
<td>$^{147}$Sm</td>
<td>14.99</td>
<td>$\alpha$</td>
<td>$1.06 \times 10^{11}$</td>
<td>$^{143}$Nd</td>
</tr>
<tr>
<td>$^{148}$Sm</td>
<td>11.24</td>
<td>$\alpha$</td>
<td>$7 \times 10^{15}$</td>
<td>$^{144}$Nd→$^{140}$Ce</td>
</tr>
</tbody>
</table>

(Continued)
3.5 SOME EXTINCT ISOTOPES

TABLE 3.2 (Continued)  DECRYPT MECHANISMS AND HALF-LIVES

<table>
<thead>
<tr>
<th>Isotope</th>
<th>% of Element</th>
<th>Decay Mechanism</th>
<th>Half-Life (years)</th>
<th>Decay Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>150Nd</td>
<td>5.6</td>
<td>2β</td>
<td>$6.7 \times 10^{18}$</td>
<td>150Sm</td>
</tr>
<tr>
<td>153Eu</td>
<td>47.81</td>
<td>$\alpha, \beta$</td>
<td>$5 \times 10^{18}$</td>
<td>157Pm$\rightarrow$147Sm</td>
</tr>
<tr>
<td>152Gd</td>
<td>0.2</td>
<td>2α</td>
<td>$1.08 \times 10^{14}$</td>
<td>148Sm$\rightarrow$144Nd</td>
</tr>
<tr>
<td>156Dy</td>
<td>0.0524</td>
<td>α</td>
<td>$2 \times 10^{14}$</td>
<td>152Gd</td>
</tr>
<tr>
<td>174Hf</td>
<td>0.162</td>
<td>α</td>
<td>$2.0 \times 10^{15}$</td>
<td>170Yb</td>
</tr>
<tr>
<td>176Lu</td>
<td>2.59</td>
<td>β</td>
<td>$3.85 \times 10^{10}$</td>
<td>176Hf</td>
</tr>
<tr>
<td>180W</td>
<td>0.12</td>
<td>α</td>
<td>$1.8 \times 10^{18}$</td>
<td>176Hf</td>
</tr>
<tr>
<td>181Os</td>
<td>1.89</td>
<td>α</td>
<td>$2 \times 10^{15}$</td>
<td>182W</td>
</tr>
<tr>
<td>187Re</td>
<td>62.6</td>
<td>99.99% β, 0.01% α</td>
<td>$4.12 \times 10^{10}$</td>
<td>187Os, 187Ta</td>
</tr>
<tr>
<td>190Pt</td>
<td>0.014</td>
<td>α</td>
<td>$6.5 \times 10^{11}$</td>
<td>186Os</td>
</tr>
<tr>
<td>204Pb</td>
<td>1.35</td>
<td>α</td>
<td>$1.4 \times 10^{17}$</td>
<td>200Hg</td>
</tr>
<tr>
<td>209Bi</td>
<td>100</td>
<td>α</td>
<td>$1.9 \times 10^{19}$</td>
<td>205Tl</td>
</tr>
<tr>
<td>232Th</td>
<td>100</td>
<td>$6\alpha + 4\beta$</td>
<td>$1.4010 \times 10^{10}$</td>
<td>208Pb (final)</td>
</tr>
<tr>
<td>235U</td>
<td>0.7201</td>
<td>$7\alpha + 4\beta$</td>
<td>$7.0381 \times 10^{8}$</td>
<td>207Pb (final)</td>
</tr>
<tr>
<td>238U</td>
<td>99.2743</td>
<td>$8\alpha + 6\beta, 5.4 \times 10^{-5}%$ fission</td>
<td>$4.4683 \times 10^{9}$</td>
<td>209Pb (final)</td>
</tr>
</tbody>
</table>

Note: α, alpha particle emission; β, electron emission; β⁺, positron emission; K, electron capture [normally from the innermost (K) shell of orbital electrons].

TABLE 3.3  EXTINCT ISOTOPES WITH DECAY PRODUCTS THAT ARE IDENTIFIABLE IN METEORITES OR PROVIDE ISOTOPIC CLUES TO EARLY SOLAR SYSTEM PROCESSES

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Decay Mechanism</th>
<th>Half-Life (years)</th>
<th>Decay Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>22Na</td>
<td>β⁺</td>
<td>2.603</td>
<td>22Ne</td>
</tr>
<tr>
<td>26Al</td>
<td>85% β⁺, 15% K</td>
<td>$7.17 \times 10^{5}$</td>
<td>26Mg</td>
</tr>
<tr>
<td>60Fe</td>
<td>2β</td>
<td>$3 \times 10^{5}$</td>
<td>60Ni via 60Co</td>
</tr>
</tbody>
</table>

(Continued)
### TABLE 3.4 ISOTOPES PRODUCED BY COSMIC RAYS OR RADIOACTIVE DECAY

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Decay Mechanism</th>
<th>Half-Life</th>
<th>Decay Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron</td>
<td>β</td>
<td>611 s (10.18 minutes)</td>
<td>$^1\text{H}$</td>
</tr>
<tr>
<td>$^3\text{H}$, tritium</td>
<td>β</td>
<td>12.32 years</td>
<td>$^3\text{He}$</td>
</tr>
<tr>
<td>$^7\text{Be}$</td>
<td>K</td>
<td>53.22 days</td>
<td>$^7\text{Li}$</td>
</tr>
<tr>
<td>$^10\text{Be}$</td>
<td>β</td>
<td>$1.39 \times 10^6$ years</td>
<td>$^{10}\text{B}$</td>
</tr>
<tr>
<td>$^{14}\text{C}$</td>
<td>β</td>
<td>5730 years</td>
<td>$^{14}\text{N}$</td>
</tr>
<tr>
<td>$^{22}\text{Na}$</td>
<td>β</td>
<td>2.603 years</td>
<td>$^{22}\text{Ne}$</td>
</tr>
<tr>
<td>$^{32}\text{Si}$</td>
<td>2β</td>
<td>153 years</td>
<td>$^{32}\text{S}$ via $^{32}\text{P}$</td>
</tr>
<tr>
<td>$^{32}\text{P}$</td>
<td>β</td>
<td>14.263 days</td>
<td>$^{32}\text{S}$</td>
</tr>
<tr>
<td>$^{33}\text{P}$</td>
<td>β</td>
<td>25 days</td>
<td>$^{33}\text{S}$</td>
</tr>
<tr>
<td>$^{35}\text{S}$</td>
<td>β</td>
<td>87.5 days</td>
<td>$^{35}\text{Cl}$</td>
</tr>
<tr>
<td>$^{36}\text{Cl}$</td>
<td>98.1% β, 1.9% K</td>
<td>3.01 × 10$^5$ years</td>
<td>$^{36}\text{Ar}$, $^{36}\text{S}$</td>
</tr>
<tr>
<td>$^{37}\text{Ar}$</td>
<td>K</td>
<td>35 days</td>
<td>$^{37}\text{Cl}$</td>
</tr>
</tbody>
</table>

(Continued)
Nuclear fission, principally of $^{235}\text{U}$ and $^{239}\text{Pu}$, results in fragments with unequal atomic masses in ranges 85–110 and 125–155. Statistics of the fragments depend somewhat on the fissioning isotopes and on conditions such as energies of incident neutrons. Each fission event also produces two or three neutrons and, in a few cases, other small fragments such as tritium ($^3\text{H}$). The products are all neutron-rich, making them radioactive emitters of $\beta$ particles (energetic electrons). There is a very wide range of radioactive fission products. Table 3.5 lists the ones of particular environmental concern on account of their abundances and likelihood of ingestion.

Releases from nuclear accidents also include isotopes of the actinides (elements close to thorium, uranium and plutonium in the periodic table), as well as unfissioned $^{235}\text{U}$ and $^{239}\text{Pu}$ (half-life 24,100 years).

The total intensity of radiation from fission products, $R$, decreases with time as a sum of numerous exponential decays, with complications arising from secondary decays. A rough empirical representation for fallout radiation at an open site, derived largely from Chernobyl data, is

$$R = R_1 t^{-1/2} \quad (3.1)$$

where $t$ is time in days, starting at day 1, when the intensity was $R_1$. This simple equation is a useful approximation for $t = 1$ day to 10,000 days (27.4 years). In the

### Table 3.4 (Continued) ISOTOPES PRODUCED BY COSMIC RAYS OR RADIOACTIVE DECAY

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Decay Mechanism</th>
<th>Half-Life</th>
<th>Decay Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{39}\text{Ar}$</td>
<td>$\beta$</td>
<td>270 years</td>
<td>$^{39}\text{K}$</td>
</tr>
<tr>
<td>$^{41}\text{Ca}$</td>
<td>K</td>
<td>$1.02 \times 10^5$ years</td>
<td>$^{41}\text{K}$</td>
</tr>
<tr>
<td>$^{53}\text{Mn}$</td>
<td>K</td>
<td>$3.7 \times 10^6$ years</td>
<td>$^{53}\text{Cr}$</td>
</tr>
<tr>
<td>$^{234}\text{U}$</td>
<td>$\alpha$</td>
<td>$2.47 \times 10^5$ years</td>
<td>$^{230}\text{Th} \rightarrow ^{206}\text{Pb}$</td>
</tr>
</tbody>
</table>

### Table 3.5 ENVIRONMENTALLY PROBLEMATIC FISSION PRODUCTS

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$^{90}\text{Sr}$</th>
<th>$^{137}\text{Cs}$</th>
<th>$^{89}\text{Sr}$</th>
<th>$^3\text{H}$</th>
<th>$^{140}\text{Ba}$</th>
<th>$^{131}\text{I}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-life</td>
<td>28 years</td>
<td>30 years</td>
<td>15 days</td>
<td>13 years</td>
<td>128 days</td>
<td>8.05 days</td>
</tr>
<tr>
<td>Ingestion</td>
<td>30%</td>
<td>~100%</td>
<td>30%</td>
<td>High$^a$</td>
<td>5%</td>
<td>100%</td>
</tr>
</tbody>
</table>

$^a$ Readily absorbed but also generally quickly excreted.
much longer term, this relationship will fail because fission products all have half-lives of either less than 100 years or more than 200,000 years and the half-life distribution of still active isotopes will change dramatically.

### 3.8 RADIOGENIC HEAT

#### TABLE 3.6 THERMALLY IMPORTANT RADIOACTIVE ISOTOPES

<table>
<thead>
<tr>
<th>Isotope</th>
<th>μW/kg</th>
<th>μW/kg of Element</th>
<th>Total Earth Content (kg)</th>
<th>Heat (10(^{12}) W)</th>
<th>Now</th>
<th>4.5 × 10(^9) years ago</th>
<th>In 10(^9) Years’ Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{238})U</td>
<td>95.0</td>
<td>94.35</td>
<td>15.02 × 10(^{16})</td>
<td>14.25</td>
<td>28.6</td>
<td>12.2</td>
<td></td>
</tr>
<tr>
<td>(^{235})U</td>
<td>562.0</td>
<td>4.05</td>
<td>0.11 × 10(^{16})</td>
<td>0.60</td>
<td>50.1</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>(^{232})Th</td>
<td>26.6</td>
<td>26.6</td>
<td>55.98 × 10(^{16})</td>
<td>14.87</td>
<td>18.6</td>
<td>14.1</td>
<td></td>
</tr>
<tr>
<td>(^{40})K</td>
<td>30.0</td>
<td>0.00350</td>
<td>8.06 × 10(^{20}) (total K)</td>
<td>2.82</td>
<td>34.2</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Total heat</td>
<td></td>
<td></td>
<td></td>
<td>31.2</td>
<td>132</td>
<td>28.1</td>
<td></td>
</tr>
</tbody>
</table>

#### TABLE 3.7 AVERAGE RADIOGENIC HEAT IN EARTH MATERIALS

<table>
<thead>
<tr>
<th>Material</th>
<th>Concentration ppm by mass</th>
<th>Heat (10(^{-12}) W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U</td>
<td>Th</td>
</tr>
<tr>
<td>Igneous rocks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Granites</td>
<td>4.6</td>
<td>18</td>
</tr>
<tr>
<td>Alkali basalts</td>
<td>0.75</td>
<td>2.5</td>
</tr>
<tr>
<td>Tholeiitic basalts</td>
<td>0.11</td>
<td>0.04</td>
</tr>
<tr>
<td>Eclogites</td>
<td>0.035</td>
<td>0.15</td>
</tr>
<tr>
<td>Peridotites</td>
<td>0.006</td>
<td>0.02</td>
</tr>
<tr>
<td>Meteorites</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbonaceous Chondrites</td>
<td>0.020</td>
<td>0.070</td>
</tr>
<tr>
<td>Ordinary Chondrites</td>
<td>0.015</td>
<td>0.046</td>
</tr>
<tr>
<td>Iron Meteorites</td>
<td>Nil</td>
<td>Nil</td>
</tr>
<tr>
<td>Moon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apollo samples</td>
<td>0.23</td>
<td>0.85</td>
</tr>
<tr>
<td>Global averages</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crust</td>
<td>1.2</td>
<td>4.5</td>
</tr>
<tr>
<td>Mantle</td>
<td>0.029</td>
<td>0.109</td>
</tr>
<tr>
<td>Core</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Whole Earth</td>
<td>0.025</td>
<td>0.093</td>
</tr>
</tbody>
</table>