18.0 Review: Recall our discussions of atoms and nuclei in Chapter 2.

- **Comparing Atoms and Nuclei**

<table>
<thead>
<tr>
<th>Property</th>
<th>Atom</th>
<th>Nucleus</th>
<th>Electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>~10^{-8} cm</td>
<td>~10^{-13} cm</td>
<td>varies</td>
</tr>
<tr>
<td>Charge</td>
<td>0</td>
<td>+1 to +118</td>
<td>-1</td>
</tr>
<tr>
<td>Mass</td>
<td>(1.67 – 400)x10^{-24} g</td>
<td>9x10^{-28} g</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>(0.1 – 20) g/cm^3</td>
<td>~2x10^{14} g/cm^3</td>
<td>varies</td>
</tr>
</tbody>
</table>

- **Components of the Atom**

<table>
<thead>
<tr>
<th>Property</th>
<th>Proton</th>
<th>Neutron</th>
<th>Electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>+1</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>Mass (AMU)</td>
<td>1</td>
<td>1</td>
<td>5x10^{-4}</td>
</tr>
<tr>
<td>Mass (g)</td>
<td>1.67493x10^{-24}</td>
<td>1.67262x10^{-24}</td>
<td>9.11x10^{-28}</td>
</tr>
</tbody>
</table>

“Atomic” Symbol:

\[ ^1 \text{H}, ^0 \text{n}, ^{-1} \text{e} \]

- **A Chemists’ Model of the Atom:**

- An atom consists of a positively charged nucleus surrounded by electrons. The charges on the electrons exactly balance the charge on the nucleus so that an atom has no charge.
- A nucleus consists of 1 or more protons and 0 or more neutrons bound together by nuclear forces (strong enough to overcome the mutual repulsions of the electrons).
- The chemical properties of atoms are determined by the number of protons in the nucleus, but do not depend on the number of neutrons.

- **Definitions and Notation**
• **Atomic Number:** The *Atomic Number* of an element is the *number of protons* in the nuclei of each of its atoms. The symbol for atomic number is Z. (Of necessity, the atomic number is equal to the charge on the nucleus.)

• **Nuclide:** *Nuclide* refers to a particular combination of a *number of protons with a number of neutrons* to form a nucleus. For example, the most common nuclide of carbon contains 6 protons and 6 neutrons in each of its nuclei, and the most common nuclide of oxygen contains 8 protons and 8 neutrons.

• **Mass Number:** The mass number of a nuclide is the sum of its number of protons and its number of neutrons. For example, the most common nuclide of carbon has a mass number of 12 (6 protons + 6 neutrons), and the most common nuclide of oxygen has a mass number of 16 (8 protons and 8 neutrons). The symbol for mass number is A.

• **Neutron Count:** By definition, this is simply the difference between the mass number and the atomic number:

\[
\text{number of neutrons} = A - Z
\]

• **Isotopes:** Any time an element has *two or more kinds of nuclides* (i.e., nuclides with the same number of protons but different numbers of neutrons) we refer to the set of nuclides as *isotopes* of that element. (We do not use the term, isotope, as a synonym for a single nuclide.)

• **Atomic Symbols Incorporating the Mass Number and the Atomic Number:** If we have a nuclide of an element with the atomic symbol, X, the atomic number, Z, and the mass number, A, we write the atomic symbol for the nuclide as:

\[
\frac{A}{Z} X
\]

For example, the three different nuclides that comprise the isotopes of carbon (i.e., carbon-12, carbon-13, and carbon-14) have the symbols

\[
^{12}_6 C, \quad ^{13}_6 C, \quad \text{and} \quad ^{14}_6 C
\]

Since the atomic number determines the atomic symbol for the element, and vice versa, the atomic symbols for nuclides often omit the atomic number. Thus the symbols for the isotopes of carbon are sometimes written:

\[
^{12} C, \quad ^{13} C, \quad \text{and} \quad ^{14} C
\]
• **Deuterium and Tritium:** The heavy isotopes of hydrogen, hydrogen-2 and hydrogen-3, have special names:

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Name</th>
<th>Symbol</th>
<th>Alternate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen-1</td>
<td>Hydrogen</td>
<td>( ^1H )</td>
<td></td>
</tr>
<tr>
<td>Hydrogen-2</td>
<td>Deuterium</td>
<td>( ^2H )</td>
<td>( ^2D )</td>
</tr>
<tr>
<td>Hydrogen-3</td>
<td>Tritium</td>
<td>( ^3H )</td>
<td>( ^3T )</td>
</tr>
</tbody>
</table>

### 18.1 Nuclear Stability and Radioactive Decay:

Over 85% of all known nuclides are unstable, meaning they are subject to radioactive decay.

- **Thermodynamic Instability:** *Thermodynamic instability* refers to a condition where *some combination of the constituents* of a given unstable nuclide is *more stable* than the nuclide itself. In other words, the reaction to convert the nuclide to the other combination would be accompanied by a release of energy (\( \Delta E < 0 \)).

- **Kinetic Instability:** *Kinetic instability* refers to the *probability* that a thermodynamically unstable nucleus *will undergo decomposition*. We refer to this decomposition process as *radioactive decay*.

- **Zone of Stability:** If we make a graph of the neutron count \((A - Z)\) versus the atomic number \((Z)\) for all known nuclides, we get Figure 18.1. The slope of this plot gives us the neutron-to-proton ratio versus atomic number:
The heavy red points indicate the positions of the 279 known, stable nuclides; hence the zone they occupy on the graph is called the zone of stability, while the gray dots mark the positions of unstable nuclides. Notice how the neutron-to-proton ratio is nearly 1:1 for the 

**FIGURE 18.1**
The zone of stability. The red dots indicate the nuclides that do not undergo radioactive decay. Note that as the number of protons in a nuclide increases, the neutron/proton ratio required for stability also increases.
stable nuclides of the lightest elements ($^{4}\text{He}$, $^{6}\text{Li}$, $^{12}\text{C}$, $^{16}\text{O}$), but that as the atomic number increases, the necessary neutron-to-proton ratio also increases, reaching a value of 1.53 for $^{202}\text{Hg}$.

- **Radioactive Decay:** Some important observations:
  - **Neutron-Proton Ratio:** As the atomic number increases, the neutron-proton ratio necessary to make stable nuclides also increases, as seen above.
  - **Large Atomic Numbers:** All known nuclides with atomic numbers exceeding 83 (the element, Bismuth) are radioactively unstable.
  - **Even Numbers:** Nuclides with even numbers of protons and neutrons are more likely to be stable than those with odd numbers of either, or especially both. See Table 18.1.

<table>
<thead>
<tr>
<th>Number of Protons</th>
<th>Number of Neutrons</th>
<th>Number of Stable Nuclides</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Even</td>
<td>Even</td>
<td>168</td>
<td>$^{12}\text{C}$, $^{16}\text{O}$</td>
</tr>
<tr>
<td>Even</td>
<td>Odd</td>
<td>57</td>
<td>$^{13}\text{C}$, $^{47}\text{Ti}$</td>
</tr>
<tr>
<td>Odd</td>
<td>Even</td>
<td>50</td>
<td>$^{19}\text{F}$, $^{23}\text{Na}$</td>
</tr>
<tr>
<td>Odd</td>
<td>Odd</td>
<td>4</td>
<td>$^{2}\text{H}$, $^{6}\text{Li}$</td>
</tr>
</tbody>
</table>

Note: Even numbers of protons and neutrons seem to favor stability.

- **Magic Numbers:** There are certain specific numbers (called *magic numbers*) of protons or neutrons that make for especially stable nuclides. These magic numbers are 2, 8, 20, 28, 50, 82, and 126. These numbers are akin to the numbers of electrons (2, 10, 18, 36, 54, and 86) that give the noble gases their special chemical unreactivity.

- **Unstable Nuclides Above the Zone of Stability:** One can surmise that an unstable nuclide above the zone of stability (i. e., whose neutron-to-proton ratio is “too high”) “would like” to decay so as to reduce its number of neutrons and/or increase its number of protons.

- **Unstable Nuclides Below the Zone of Stability:** One can also surmise that an unstable nuclide below the zone of stability (i. e., whose neutron-to-proton ratio is “too low”) “would like” to decay so
as to increase its number of neutrons and/or decrease its number of protons.

- **Unstable Nuclides Above Atomic Number 83:** Another surmise one could make is that a(n unstable) nuclide whose atomic number exceeds 83 “would like” to decay by a process that reduces its number of protons, even if it also causes a decrease in its number of neutrons.

- **Types of Radioactive Decay Processes:** The earliest radioactive decay processes to be described were named, logically enough, alpha emission, beta emission, and gamma emission. Later studies revealed the identities of the emitted particles:

<table>
<thead>
<tr>
<th>Process</th>
<th>Type of Particle</th>
<th>Atomic Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha (α) emission</td>
<td>helium nucleus</td>
<td>$^4_2\text{He}$</td>
</tr>
<tr>
<td>Beta (β) emission</td>
<td>electron</td>
<td>$^0_{-1}\text{e}$</td>
</tr>
<tr>
<td>Gamma (γ) emission</td>
<td>high-energy photon</td>
<td>$^0_0\text{γ}$</td>
</tr>
</tbody>
</table>

- **Alpha Particle Emission:** In alpha particle emission, an unstable nuclide emits a helium nucleus. Many nuclides of heavy radioactive elements decay primarily by alpha particle emission. Some examples:

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Symbol</th>
<th>Equation</th>
<th>Changes in Numbers of Nucleons (ΔA)</th>
<th>Protons (ΔZ)</th>
<th>Neutrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>uranium-238</td>
<td>$^{238}_{92}\text{U}$</td>
<td>$^{238}<em>{92}\text{U} \rightarrow ^4_2\text{He} + ^{234}</em>{90}\text{Th}$</td>
<td>-4</td>
<td>-2</td>
<td>-2</td>
</tr>
<tr>
<td>thorium-230</td>
<td>$^{230}_{90}\text{Th}$</td>
<td>$^{230}<em>{90}\text{Th} \rightarrow ^4_2\text{He} + ^{226}</em>{88}\text{Ra}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Spontaneous Fission:** Spontaneous fission is a decay process in which a heavy nuclide divides into two lighter nuclides of similar mass numbers.

- **Beta Particle Emission:** In beta particle emission, an unstable nuclide emits an electron. There is no change in mass number; effectively a neutron is converted to a proton, and the neutron-to-proton ratio gets lowered. Thus it is a common decay mode for nuclides above the zone of stability. Here are examples of nuclei that undergo beta decay:
Changes in Numbers of Nuclide Symbol Equation Nucleons $(\Delta A)$ Protons $(\Delta Z)$ Neutrons

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Symbol</th>
<th>Equation</th>
<th>Nucleons $(\Delta A)$</th>
<th>Protons $(\Delta Z)$</th>
<th>Neutrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>thorium-234</td>
<td>$^{234}_{90}$Th</td>
<td>$^{234}<em>{90}$Th $\rightarrow$ $^0_1$e + $^{234}</em>{91}$Pa</td>
<td>0</td>
<td>+1</td>
<td>-1</td>
</tr>
<tr>
<td>iodine-131</td>
<td>$^{131}_{53}$I</td>
<td>$^{131}<em>{53}$I $\rightarrow$ $^0_1$e + $^{131}</em>{54}$Xe</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Gamma Ray Emission:** Gamma rays are simply high-energy photons lacking either mass or charge. Gamma rays often accompany other modes of decay. For example, the alpha decay of uranium-238 emits two gamma ray photons along with its other decay products:

  **Nuclide** | **Symbol** | **Equation**        | **Changes in Numbers** |
  ---------- |------------|---------------------|------------------------|
  uranium-238 | $^{238}_{92}$U | $^{238}_{92}$U $\rightarrow$ $^4_2$He + $^{234}_{90}$Th + $^0_0$$\gamma$ |                      |

- **Positron Emission:** In positron emission, an unstable nuclide emits a positron (positive electron). There is no change in mass number; effectively a proton is converted to a neutron, and the neutron-to-proton ratio gets raised. Thus it is a common decay mode for nuclides below the zone of stability. Sodium-22 is an example of a nuclide that undergoes positron emission:

  **Nuclide** | **Symbol** | **Equation**        | **Changes in Numbers** |
  ---------- |------------|---------------------|------------------------|
  sodium-22  | $^{22}_{11}$Na | $^{22}_{11}$Na $\rightarrow$ $^0_1$e + $^{22}_{10}$Ne | 0 -1 +1               |

  The positron not only has the opposite charge of an electron, it is actually the antiparticle of the electron. This means if a positron collides with an electron, both particles are annihilated and their mass is converted to high-energy photons:

  $^0_1$e + $^0_1$e $\rightarrow$ $^2_0$$\gamma$

- **Electron Capture:** Electron capture changes the nucleus in the same manner as positron emission – a proton gets converted to a neutron, and the neutron-to-proton ratio gets raised. The essential difference is that one of the innermost electrons gets captured by the nucleus and is a reactant in the decay process. An example is the decay of mercury-201 to gold. Gamma rays are always produced in electron capture processes.
Changes in Numbers of Nuclide Symbol Equation Nucleons (ΔA) Protons (ΔZ) Neutrons

mercury-201 201\textsuperscript{80} \textit{Hg} → 201\textsuperscript{79} \textit{Au} + 0 {γ} \quad 0 \quad -1 \quad +1

- **Sample Exercise 18.1** (pp. 844-5): Write balanced equations for the following nuclear decay processes:
  - (a) \textsuperscript{11}_6 \textit{C} produces a positron.
    
    We write out the full equation for the reaction, expressing the other product as \( \frac{A}{Z}X \):
    
    \[
    \textsuperscript{11}_6 \textit{C} \rightarrow 0 \text{e} + \frac{A}{Z}X
    \]
    
    The way to balance this equation is to make the totals on either side of the equation the same for both the A’s and the Z’s:
    
    \[
    11 = 0 + A \quad A = 11
    \]
    \[
    6 = 1 + Z \quad Z = 5
    \]
    
    And since 5 is the atomic number for boron, we substitute B in place of X:
    
    \[
    \textsuperscript{11}_6 \textit{C} \rightarrow 0 \text{e} + \textsuperscript{11}_5 \textit{B}
    \]
  
  - (b) \textsuperscript{214}_83 \textit{Bi} produces a β particle:
    
    This time we will balance the A’s and the Z’s as we write the equation:
    
    \[
    \textsuperscript{214}_83 \textit{Bi} \rightarrow 0 \text{e} + \textsuperscript{214}_84 X
    \]
    
    Now we look up atomic number 84 in the periodic table and find polonium (Po). So the result is:
    
    \[
    \textsuperscript{214}_83 \textit{Bi} \rightarrow 0 \text{e} + \textsuperscript{214}_84 \textit{Po}
    \]
  
  - (c) \textsuperscript{237}_93 \textit{Np} produces an α particle:
    
    Since the production of the α particle reduces the mass number (A) by 4 (to 233) and the atomic number (Z) by 2 (to 91 = Pa: protoactinium) we just write out the result:
    
    \[
    \textsuperscript{237}_93 \textit{Np} \rightarrow 4 \text{He} + \textsuperscript{233}_91 \textit{Pa}
    \]
Sample Exercise 18.2 (pp. 845-6): Supply the missing particle in each of the following:

(a) $^{195}_{79}Au + ? \rightarrow ^{195}_{78}Pt$

First we balance the A’s and the Z’s:

\[
195 + A = 195 \quad \Rightarrow \quad A = 0 \\
79 + Z = 78 \quad \Rightarrow \quad Z = -1
\]

The missing particle is an electron, and the process is electron capture, so the full equation is:

\[
^{195}_{79}Au + ^{0}_{-1}e \rightarrow ^{195}_{78}Pt
\]

(b) $^{38}_{19}K \rightarrow ? + ^{38}_{18}Ar$

We need a positron to balance this reaction, so the process is positron decay:

\[
^{38}_{19}K \rightarrow ^{0}_{1}e + ^{38}_{18}Ar
\]

Radioactive Decay Series: Some radioactive nuclides are relatively stable, compared to their decay products. Thus when one of these nuclides decays, the product will itself decay faster than it can accumulate. Some of these decay series (or decay chains). A good example is the decay of thorium-232, which involves chain that ends by reaching the stable nuclide, lead-208:

\[
^{232}_{90}Th \rightarrow \text{(series of decays)} \rightarrow ^{208}_{82}Pb
\]

Another good example is the decay of uranium-235 to lead-207:

\[
^{235}_{92}U \rightarrow \text{(series of decays)} \rightarrow ^{207}_{82}Pb
\]

And still another is the decay chain for uranium-238, ending with lead-206:

\[
^{238}_{92}U \rightarrow \text{(series of decays)} \rightarrow ^{206}_{82}Pb
\]

Assuming that the decay series involves only alpha and beta particle emission, let’s balance this overall equation. We start by writing:

\[
^{238}_{92}U \rightarrow ^{206}_{82}Pb + n_{\alpha}^{4}_{2}He + n_{\beta}^{0}_{-1}e
\]

Here, $n_{\alpha}$ represents the number of alpha particles and $n_{\beta}$ represents the number of beta particles emitted during the decay chain. Now we can balance the mass numbers (the A’s):

\[
238 = 206 + 4 n_{\alpha}
\]
\[
238 - 206 = 4n_\alpha \\
32 = 4n_\alpha \\
n_\alpha = 8 \\

^{238}_{92}\text{U} \rightarrow ^{206}_{82}\text{Pb} + 8^{4}_2\text{He} + n_\beta^{0}_1\text{e}
\]

And now we can balance the charges (the Z’s):

\[
92 = 82 + 8\times2 - n_\beta \\
92 = 82 + 16 - n_\beta \\
92 = 98 - n_\beta \\
92 - 98 = -n_\beta \\
-6 = -n_\beta \\
n_\beta = 6 \\

^{238}_{92}\text{U} \rightarrow ^{206}_{82}\text{Pb} + 8^{4}_2\text{He} + 6^{0}_1\text{e}
\]

The decay chain produces 8 alpha particles and 6 beta particles as by-products of the conversion of uranium-238 to lead-206.

This last chain is diagrammed in Figure 18.2, where the diagonal arrows represent alpha decay, and the horizontal arrows represent beta decay:
18.2 Kinetics of Radioactive Decay: Kinetics of radioactive decay is the answer to the question, how fast does a sample of a given kind of nuclide decay? and how does the amount of this nuclide vary over time?

- **Rate of Decay:** We will state without proving that if a certain amount of a given nuclide decays at the rate of 100 atoms per second, then twice the amount of the same nuclide will decay at the rate of 200 atoms per second. In general, the rate of decay is proportional to the
number of nuclide atoms in the sample. If \( N \) atoms of nuclide are present at a time, \( t \), and \( N_0 \) atoms were present at the (earlier) time, \( t_0 \), then the rate of decay can be expressed as minus the change in the number of nuclide atoms in one unit of time:

\[
Rate = -\frac{(N - N_0)}{(t - t_0)} = -\frac{\Delta N}{\Delta t} = kN
\]

We abbreviate the expression \((N - N_0)\) as \(\Delta N\). (Note that it has a negative value, since the number of nuclide atoms is decreasing over time.) Similarly we abbreviate the (positive) expression \((t - t_0)\) as \(\Delta t\). Thus the rate of decay is a positive quantity, and \(k\) is the rate constant for the decay process. This equation can be called the differential first order rate law.

- **Solving the Rate Equation:** Solving the rate equation is an exercise in calculus for which we will not hold you responsible. We will give you the result both now and when we test you on the kinetics of radioactive decay). The solution is called the integrated first-order rate law. In logarithmic form, it is written:

\[
\ln\left(\frac{N}{N_0}\right) = -kt
\]

Here, \( N \) is the number of nuclide atoms present at the time, \( t \), and \( N_0 \) is the number that were present at time \( t=0 \). The symbol, \( \ln \), represents taking the natural logarithm of the expression in parentheses. This expression can be written in the exponential form:

\[
\frac{N}{N_0} = e^{-kt}
\]

- **Calculations Involving Measured Decay Rates:** In radioactive decay problems, one often does not have any direct information about \( N \), \( N_0 \), or the ratio, \( N/N_0 \), but one might have information about the rates of decay at two different times. How can one use this information with the integrated first-order rate law? The answer is that one must start with the differential first order rate law and write separate expressions for the two rates:

\[
Rate = kN
\]
\[ \text{Rate}_0 = kN_0 \]

Now one can divide the first expression by the second:

\[ \frac{\text{Rate}}{\text{Rate}_0} = \frac{kN}{kN_0} = \frac{N}{N_0} \]

Thus \( N/N_0 \) can be calculated from the rates at the two different times, and the result can plugged into the integrated rate law to complete the solution of the problem. We will use this kind of calculation in Section 18.4 when we study radiocarbon dating.

- **Half-Life:** The half-life (written \( t_{1/2} \)) of a nuclide is defined as the time required for half of a sample of that nuclide to decay. (This is the time at which \( N = 0.5N_0 \).) We can plug this information into the logarithmic form of the rate law:

\[
\ln\left(\frac{1}{2}\right) = -kt_{1/2}
\]

\[
\ln(2) = kt_{1/2}
\]

Now we can solve for the half-life:

\[
t_{1/2} = \frac{\ln(2)}{k} = \frac{0.693}{k}
\]

- **Calculating the Rate Constant Given the Half-Life:** In many of the radioactive decay problems you will encounter, you will be provided with the half life of a radioactive decay process. Here is how to calculate the rate constant from that information:

\[
\ln\left(\frac{1}{2}\right) = -kt_{1/2}
\]

\[
\ln(2) = kt_{1/2}
\]

\[
k = \frac{\ln(2)}{t_{1/2}} = \frac{0.693}{t_{1/2}}
\]
The half-life of a decay process is constant. This is seen in the graph of the beta-particle decay process for strontium-90, illustrated in Figure 18.3. This process has a half-life of 28.8 years. Notice that the curve takes on the familiar shape of exponential decay.

![Graph of beta-particle decay process for strontium-90](image)

**FIGURE 18.3**

The decay of a 10.0-g sample of strontium-90 over time. Note that the half-life is a constant 28.8 years.

### Sample Exercise 18.3 (p. 847)

Technicium-99m is used in medical imaging to form pictures of the heart and other internal organs. Technicium-99m decays to technicium-99 by gamma-emission:

\[
^{99m}\text{Tc} \rightarrow ^{99}\text{Tc} + ^0\gamma
\]

The rate constant for this decay process is \( k = 1.16 \times 10^{-1} /\text{h} \). What is the half life of technecium-99m?

We use the equation for \( t_{1/2} \):

\[
t_{1/2} = \frac{\ln(2)}{k} = \frac{0.693}{1.16 \times 10^{-1} /\text{hr}} = 5.98 \text{ hr}
\]

Half of a sample of technecium-99m sample will decay over a period of 5.98 hours.

### Sample Exercise 18.4 (p. 848)

The half life of molybdenum-99 is 67.0 hr. How much of a 1.000 mg sample of molybdenum-99 will remain after 335 hr?
Any time you are given the half life of something and some period of elapsed time, it is a good idea to compute the number of half-lives represented by that period. In this case, the number is:

\[ \frac{335}{67.0} = 5.00 \text{ half-lives} \]

In most cases the number of half-lives has a fractional part and yields only an approximate result, but in this case we have an integer number of half-lives and we can calculate as follows:

<table>
<thead>
<tr>
<th>Half-Lives</th>
<th>Fraction Left</th>
<th>Mass Left (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1.000</td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
<td>0.500</td>
</tr>
<tr>
<td>2</td>
<td>0.25</td>
<td>0.250</td>
</tr>
<tr>
<td>3</td>
<td>0.125</td>
<td>0.125</td>
</tr>
<tr>
<td>4</td>
<td>0.0625</td>
<td>0.0625</td>
</tr>
<tr>
<td>5</td>
<td>0.03125</td>
<td>0.0313</td>
</tr>
</tbody>
</table>

Figure 18.4 is a plot of these data. As expected, the shape of the plot is exponential:

- **Range of Half-Lives:** Half-lives of radioactive nuclides can range in length from small fractions of a second to billions (or more) of years.
For example, the nuclides in the decay series for $^{238}_{92}\text{U}$ that we examined in Figure 18.2 are listed in Table 18.3:

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Particle Produced</th>
<th>Half-Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium-238 ($^{238}_{92}\text{U}$)</td>
<td>$\alpha$</td>
<td>$4.51 \times 10^9$ years</td>
</tr>
<tr>
<td>Thorium-234 ($^{234}_{90}\text{Th}$)</td>
<td>$\beta$</td>
<td>24.1 days</td>
</tr>
<tr>
<td>Protactinium-234 ($^{234}_{91}\text{Pa}$)</td>
<td>$\beta$</td>
<td>6.75 hours</td>
</tr>
<tr>
<td>Uranium-234 ($^{234}_{92}\text{U}$)</td>
<td>$\alpha$</td>
<td>$2.48 \times 10^5$ years</td>
</tr>
<tr>
<td>Thorium-230 ($^{230}_{90}\text{Th}$)</td>
<td>$\alpha$</td>
<td>$8.0 \times 10^4$ years</td>
</tr>
<tr>
<td>Radium-226 ($^{226}_{88}\text{Ra}$)</td>
<td>$\alpha$</td>
<td>$1.62 \times 10^3$ years</td>
</tr>
<tr>
<td>Radon-222 ($^{222}_{86}\text{Rn}$)</td>
<td>$\alpha$</td>
<td>3.82 days</td>
</tr>
<tr>
<td>Polonium-218 ($^{218}_{84}\text{Po}$)</td>
<td>$\alpha$</td>
<td>3.1 minutes</td>
</tr>
<tr>
<td>Lead-214 ($^{214}_{82}\text{Pb}$)</td>
<td>$\beta$</td>
<td>26.8 minutes</td>
</tr>
<tr>
<td>Bismuth-214 ($^{214}_{83}\text{Bi}$)</td>
<td>$\beta$</td>
<td>19.7 minutes</td>
</tr>
<tr>
<td>Polonium-214 ($^{214}_{84}\text{Po}$)</td>
<td>$\alpha$</td>
<td>$1.6 \times 10^{-4}$ second</td>
</tr>
<tr>
<td>Lead-210 ($^{210}_{82}\text{Pb}$)</td>
<td>$\beta$</td>
<td>20.4 years</td>
</tr>
<tr>
<td>Bismuth-210 ($^{210}_{83}\text{Bi}$)</td>
<td>$\beta$</td>
<td>5.0 days</td>
</tr>
<tr>
<td>Polonium-210 ($^{210}_{84}\text{Po}$)</td>
<td>$\alpha$</td>
<td>138.4 days</td>
</tr>
<tr>
<td>Lead-206 ($^{206}_{82}\text{Pb}$)</td>
<td>—</td>
<td>Stable</td>
</tr>
</tbody>
</table>

What is the half-life for the overall transition from uranium-238 to lead-206?

$$^{238}_{92}\text{U} \rightarrow ^{206}_{82}\text{Pb} + 8\ ^{4}_{2}\text{He} + 6\ ^{0}_{-1}\text{e}$$

One could approximate the answer by adding all the individual half-lives together. Let’s start by adding the two largest values together:
**Nuclide** | **Half-Life**  
--- | ---  
uranium-238 | $4.51 \times 10^9$ years  
uranium-234 | $2.48 \times 10^5$ years  

\[
4,510,000,000 \text{ years} = 4.51 \times 10^9 \text{ years}
\]

We need not consider any more of the steps. The half-life for the overall process is essentially the same as that of the longest individual step.

**18.3 Nuclear Synthesis:** In Section 18.1 we studied one major kind of nuclear reaction, *radioactive decay*. Radioactive decay always involves the reaction of a single nucleus, as in spontaneous fission, alpha particle emission, or beta particle emission (or the reaction of a single atom as in the case of electron capture). Nuclear synthesis (The book calls it nuclear transformation) is another kind of nuclear reaction process in which one element is transformed into another.

- **The First Observed Nuclear Transformations:** You may recall that Lord Rutherford discovered the nuclear nature of the atom by bombarding gold foil with a stream of alpha particles. When, several years later (1919), he bombarded nitrogen with alpha particles, he discovered that oxygen-17 was produced:

\[
^{14}_7 \text{N} + ^4_2 \text{He} \rightarrow ^{17}_8 \text{O} + ^1_1 \text{H}
\]

The next discovery was made in 1933 by Irene Curie and (her husband) Frederick Joliot, the transformation of aluminum to phosphorous, also brought about by alpha bombardment:

\[
^{27}_{13} \text{Al} + ^4_2 \text{He} \rightarrow ^{30}_{15} \text{P} + ^1_0 \text{n}
\]

Phosphorous-30, with its odd number of protons (15) and its odd number of neutrons (also 15) is not one of the four known stable nuclides with odd numbers both of protons and neutrons. It is a radioactive nuclide with a half-life of about 14 days, and it is not found in nature. In fact, it is the first artificial nuclide ever to be observed and characterized.

- **Particle Accelerators:** Most nuclear transformations are achieved through the use of particle accelerators. Notice that the above two examples are of collisions between pairs of positively charged particles. In order for such a pair of particles to overcome their mutual electrostatic repulsion, they must be set on a high-velocity collision course. This is what particle accelerators are designed to do.
types of particle accelerators illustrated in your text are the cyclotron and the linear accelerator.

- **The Cyclotron:**

![Cyclotron Diagram](image)

**FIGURE 18.5**
A schematic diagram of a cyclotron. The ion is introduced in the center and is pulled back and forth between the hollow D-shaped electrodes by constant reversals of the electric field. Magnets above and below these electrodes produce a spiral path that expands as the particle velocity increases. When the particle has sufficient speed, it exits the accelerator and is directed at the target nucleus.

- **The Linear Accelerator**

![Linear Accelerator Diagram](image)

**FIGURE 18.6**
Schematic diagram of a linear accelerator, which uses a changing electric field to accelerate a positive ion along a linear path. As the ion leaves the source, the odd-numbered tubes are negatively charged, and the even-numbered tubes are positively charged. The positive ion is thus attracted into tube 1. As the ion leaves tube 1, the tube polarities are reversed. Now tube 1 is positive, repelling the positive ion, and tube 2 is negative, attracting the positive ion. This process continues, eventually producing high particle velocity.
**Neutron Bombardment:** Alpha particles are not the only type of particle that can be used to achieve nuclear transformations. Neutrons (discovered in 1932) have the advantage, over bombardment with alpha and other charged particles, that they do not need to overcome electrostatic repulsion to achieve collision with a charged nucleus. This also means that they cannot be accelerated by electric fields. But it turned out that they don’t need to be. In fact, Enrico Fermi discovered that if he slowed down the neutrons in the beams he produced, they were more likely to react with their target nuclei.

When a target nuclide absorbs a neutron, it becomes initially converted to a different nuclide of the same element, but with a higher count of neutrons. This moves the target away from the zone of stability into the area that favors radioactive decay by beta emission and consequent formation of a nuclide of the element with the next higher atomic number. For example:

\[
^{18}_{8}\text{O} + ^{1}_{0}\text{n} \rightarrow ^{19}_{8}\text{O} \rightarrow ^{19}_{9}\text{F} + ^{0}_{-1}\text{e}
\]

**Transuranium Elements through Neutron Bombardment:** In 1934, Fermi hypothesized that he could subject uranium to neutron bombardment and create trans-uranium elements, i.e., elements with atomic numbers 93 and higher and not known in nature. When he ran the experiment, he thought he had produced element number 93 by the reaction:

\[
^{238}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{239}_{92}\text{U} \rightarrow ^{239}_{93}\text{Np} + ^{0}_{-1}\text{e}
\]

However, natural uranium contains about 0.7% uranium-235, and when that absorbs a neutron, it undergoes nuclear fission to produce, among other product, a highly radioactive nuclide of barium. (We'll say more about this later.) It wasn’t until 1940 that Edwin McMillan (1907-91) and Philip Abelson (1913-) confirmed the generation of neptunium-239 by neutron bombardment of uranium-238. Then the following year, Abelson and Glenn Seaborg (1912-) confirmed that neptunium-239 would undergo beta decay to generate plutonium-239:

\[
^{239}_{93}\text{Np} \rightarrow ^{239}_{94}\text{Pu} + ^{0}_{-1}\text{e}
\]

Plutonium-239 would soon be generated on an industrial scale by neutron bombardment of uranium-238. It would then be used to form the explosive heart of the atomic bomb that was dropped on Nagasaki, Japan in 1945 to help end World War II.

**Transuranium Elements through Alpha Bombardment:** It also proved possible to produce transuranium elements by alpha
bombardment. For example, the conversion of curium-242 to californium-245:

\[ ^{242}_{96}\text{Cm} + ^{4}_{2}\text{He} \rightarrow ^{245}_{98}\text{Cf} + ^{1}_{0}\text{n} \]

- **Heavy-Ion Bombardment**: Neutron bombardment and even alpha particle bombardment achieve relatively small increments in atomic numbers (and atomic masses). Achievement of higher atomic numbers requires that several steps be run in series. For example, the curium-242 to start the above reaction had to be produced by alpha bombardment of plutonium-239. And the plutonium-239 in turn was produced by neutron bombardment of uranium-238. Since the half-lives of transuranium elements tend to decrease as the atomic number increases, there comes a point where further increases in atomic number become impractical without using nuclei that are heavier than alpha particles. Fortunately, the development of higher and higher energy particle accelerators makes this possible. For example, the nuclear synthesis of californium-246:

\[ ^{238}_{92}\text{U} + ^{12}_{6}\text{C} \rightarrow ^{246}_{98}\text{Cf} + 4^1_0\text{n} \]

Some further examples of the production of transuranium elements are shown in Table 18.4 from your text:
**TABLE 18.4 Syntheses of Some of the Transuranium Elements**

<table>
<thead>
<tr>
<th>Element</th>
<th>Neutron Bombardment</th>
<th>Half-Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neptunium (Z = 93)</td>
<td>$^{238}\text{U} + _1^0\text{n} \rightarrow ^{239}\text{Np} + _{-1}^0\text{e}$</td>
<td>2.35 days ($^{239}\text{Np}$)</td>
</tr>
<tr>
<td>Plutonium (Z = 94)</td>
<td>$^{239}\text{Np} \rightarrow ^{239}\text{Pu} + _{-1}^0\text{e}$</td>
<td>24,400 years ($^{239}\text{Pu}$)</td>
</tr>
<tr>
<td>Americium (Z = 95)</td>
<td>$^{239}\text{Pu} + 2_0^1\text{n} \rightarrow ^{241}\text{Pu} \rightarrow ^{241}\text{Am} + _{-1}^0\text{e}$</td>
<td>458 years ($^{241}\text{Am}$)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Element</th>
<th>Positive-Ion Bombardment</th>
<th>Half-Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curium (Z = 96)</td>
<td>$^{239}\text{Pu} + _{2}^4\text{He} \rightarrow ^{242}\text{Cm} + _{-1}^0\text{n}$</td>
<td>163 days ($^{242}\text{Cm}$)</td>
</tr>
<tr>
<td>Californium (Z = 98)</td>
<td>$^{242}\text{Cm} + _{2}^4\text{He} \rightarrow ^{245}\text{Cf} + _{-1}^0\text{n}$</td>
<td>44 minutes ($^{245}\text{Cf}$)</td>
</tr>
</tbody>
</table>
  or $^{238}\text{U} + _{6}^{12}\text{C} \rightarrow ^{246}\text{Cf} + 4_0^1\text{n}$
| Rutherfordium (Z = 104) | $^{240}\text{Cf} + _{6}^{12}\text{C} \rightarrow ^{257}\text{Rf} + 4_0^1\text{n}$  |            |
| Dubnium (Z = 105)   | $^{240}\text{Cf} + _{7}^{15}\text{N} \rightarrow ^{260}\text{Db} + 4_0^1\text{n}$ |            |
| Seaborgium (Z = 106) | $^{240}\text{Cf} + _{8}^{18}\text{O} \rightarrow ^{263}\text{Sg} + 4_0^1\text{n}$ |            |

**18.4 Detection and Uses of Radioactivity**

- **Measuring Radioactivity:** The two most familiar instruments for making radioactivity measurements are the Geiger – Müller counter (also called simply Geiger counter) and the scintillation counter.
  
- **The Geiger – Müller Counter:** The Geiger – Müller counter takes advantage of the fact that radioactive decay produces high-energy particles that can ionize the matter through which they pass. (Thus radiation like that produced by radioactive decay is often called **ionizing radiation**.) The probe of a Geiger – Müller counter is filled with argon gas, whose atoms will ionize when struck by high-energy particles:

  ![Ionization Equation]

  When the Geiger – Müller counter is turned on, it applies an electric potential across the argon tube. Since neutral argon gas does not
conduct electricity, there is normally no flow of current across the tube. However current will flow momentarily each time an ion is produced by a high-energy particle. (The electric current converts the argon ion back to a neutral atom, thus shutting itself off.) Each time when there is current flow can be considered an “event,” and these events can be counted and interpreted as the rate of radioactive decay of the decay source. Figure 18.7 illustrates how a Geiger – Müller counter works.

![Geiger-Müller counter diagram]

**FIGURE 18.7**
A schematic representation of a Geiger–Müller counter. The high-energy radioactive particle enters the window and ionizes argon atoms along its path. The resulting ions and electrons produce a momentary current pulse, which is amplified and counted.

- **The Scintillation Counter:** The detector in a scintillation counter is zinc sulfide, which emits light when struck by a high-energy particle. A photocell counts each flash from the detector and thus measures the rate of radioactive decay of the decay source.

- **Radioactive Dating:** Under certain conditions, measurements of radioactivity and/or analytical measurements of the amounts of radioactive materials in a sample can be used to date the sample, i. e., to determine how old it is. We will discuss carbon-14 dating and dating by radioactivity.

- **Carbon-14 Dating:** *Carbon-14 dating* (also known as *radiocarbon dating*) can be used to determine the ages of ancient articles made from wood or fabric. The technique is based on measuring the ratio of carbon-14 to carbon-12 in the article. It works because carbon-14 is radioactive and decays with a half-life of 5,730 years. In principle, articles up to 10,000 and more years old can be dated by this technique.
How It Works: Carbon-14 is generated when high-energy neutrons from space (a component of cosmic rays) collide with atmospheric nitrogen-14:

\[ ^{14}_7 \text{N} + ^{1}_0 \text{n} \rightarrow ^{14}_6 \text{C} + ^{1}_1 \text{H} \]

The resulting carbon-14 is radioactive, and it undergoes decay by beta particle emission:

\[ ^{14}_6 \text{C} \rightarrow ^{14}_7 \text{N} + ^{0}_{-1} \text{e} \]

Over the centuries, the rates of these two reactions have become equal, and the amount of atmospheric carbon-14 has reached a constant (so-called steady-state) value.

The resulting atoms of carbon-14 are chemically reactive and they readily combine with atmospheric oxygen to make carbon-14 dioxide, a radioactive molecule with the same chemistry as ordinary carbon dioxide. Through photosynthesis, it is incorporated into biomass (including wood and plant fiber). As long as the biomass remains alive, its ratio of carbon-14 to carbon-12 will match that of the atmosphere through replenishment of its carbon content. However, when the biomass dies, its carbon-14 will begin to decay without replenishment while its carbon-12 content remains constant. Since the decay process of carbon-14 has a half-life of 5,730 years, the carbon-14 to carbon-12 ratio of a sample of this biomass will fall to half its initial value after 5,730 years have elapsed. The decay rate of its carbon-14 content will also fall to half the initial value over this 5,730 year period since the rate of decay is proportional to its carbon-14 content.

Systematic Errors in Carbon Dating: The half-life of carbon-14 is a well-established number, so its use does not introduce any systematic errors into radiocarbon dating results. However, what if the atmospheric ratio of carbon-14 to carbon-12 changes over time, and we try to use the current ratio in our dating calculation? We get a systematic error.

Suppose the cosmic ray neutron flux 5,730 years ago were 20% lower than it is now. This would have made the carbon-14 to carbon-12 ratio 20% lower at that time. Our measurement today of the carbon-14 to carbon-12 ratio in our 5,730 year old wood sample would be 50% of that lower starting value, and it would be 40% of the current value of the ratio. Thus we would overestimate the age of the sample.
And suppose that the carbon-12 content of the atmosphere (i.e., \(^{12}\text{CO}_2\)) were higher today than it was 5,730 years ago. This is probably the case, due to mankind’s burning of fossil fuels, whose carbon is so old that all its original carbon-14 has long since decayed. Suppose also, that the cosmic ray neutron flux has remained constant. In this case we would underestimate the age of our sample.

**Corrections for Systematic Errors:** Fortunately, there are sources of ancient wood whose ages can be determined by counting tree rings (a technique called *dendrochronology*). Samples of the wood of giant sequoias and bristlecone pines can thus be dated as far back as 5,000 years by tree-ring counting. Then radiocarbon dating of the same samples can be used to compute correction factors that can be used to calibrate other radiocarbon dating results.

- **Sample Exercise 18.5** (pp. 853-4): The remnants of an ancient fire showed a carbon-14 decay rate of 3.1 counts per minute per gram of carbon. Assuming that freshly-cut wood decays at a rate of 13.6 counts per minute (after correcting for changes in the atmospheric carbon-14 to carbon-12 ratio over time), calculate the age of the remains. The half-life of carbon-14 is 5,730 years.

Recall that the decay rate \((\text{Rate})\) of our ancient sample is proportional to the number \((N)\) of carbon-14 nuclides it contains:

\[
\text{Rate} = kN
\]

And similarly that the decay rate \((\text{Rate}_0)\) is proportional to its number \((N_0)\) of carbon-14 nuclides:

\[
\text{Rate}_0 = kN_0
\]

Thus we can compute the ratio of the two rates:

\[
\frac{\text{Rate}}{\text{Rate}_0} = \frac{kN}{kN_0}
\]

Now we can let the \(k\)'s cancel out, and we can plug in our rate measurements:

\[
\frac{N}{N_0} = \frac{3.1}{13.6}
\]
This gives us the input we need in order to use the integrated rate law:

\[
\ln \left( \frac{N}{N_0} \right) = -kt
\]

We can compute the rate constant, \( k \), from the half-life:

\[
k = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2}{5730 \text{ yr}}
\]

Now we can solve the rate law for the time, \( t \), and plug in our numbers:

\[
t = -\frac{1}{k} \ln \left( \frac{N}{N_0} \right) = -\frac{1}{\left( \frac{\ln 2}{t_{1/2}} \right)} \ln \left( \frac{N}{N_0} \right) = -t_{1/2} \ln 2 \ln \left( \frac{N}{N_0} \right)
\]

\[
t = -\frac{5730 \text{ yr}}{\ln 2} \ln \left( \frac{3.1}{13.6} \right) = 12,000 \text{ yr}
\]

We can check to see if our result makes sense. Our quantity \( (N/N_0) \) would be 0.25 after two half-lives (11,460 yr) and 0.125 after 3 (17,190 yr). Its actual value is \( (3.1/13.6) = 0.23 \), so we expect that the answer would be slightly more than 2 half lives, in good agreement with our result of 12,000 years.

- **Radiocarbon Dating by Mass Spectrometry:** “Conventional” radiocarbon dating requires that samples be burned with recovery of carbon dioxide and measurement of the radioactive decay rates. This requires relatively large samples (up to several grams). Mass spectrometry has the advantages of requiring much smaller samples (around 1 milligram) and yielding direct and accurate measurements of the carbon-12 to carbon-14 ratios.

- **Dating by Radioactivity:** Carbon-14 is not the only radioactive nuclide that can be used for age measurements. For example, the decay of uranium-238, eventually producing lead-206, is useful
under some circumstances for making estimates of the age of uranium-containing rocks. Since uranium-238 has a half-life (4.5 billion years) that is nearly as long as the age of the earth, it can be used to determine the ages of some really old rocks. And if an even longer half-life is needed, lutecium-176 might be the answer, with a half-life of over 37 billion years.

• **Sample Exercise 18.6** (pp. 854-5): A rock containing uranium-238 and lead-206 was analyzed to determine its approximate age. The analysis showed that the ratio of lead-206 atoms to uranium-238 atoms was 0.115. You may assume that there was no lead originally present, that all of the lead generated by the decay chain is still present in the sample, and that the content of the intermediate nuclides in the decay chain is negligible. The half-life of uranium-238 is $4.5 \times 10^9$ years. Estimate the age of the rock.

We can use the integrated first order rate law:

$$\ln \left( \frac{N}{N_0} \right) = -kt$$

And we can compute the rate constant from the half-life:

$$k = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2}{4.5 \times 10^9 \text{ yr}}$$

Our measured lead-206 to uranium-238 ratio is the amount of lead produced by uranium-238 decay divided by the remaining uranium-238 that has not decayed.

$$0.115 = \frac{\text{atoms of } ^{206}\text{Pb now present}}{\text{atoms of } ^{238}\text{U now present}}$$

The present number of uranium-238 atoms is the value of $N$ that we need for the rate law equation. But for $N_0$ we need the number of uranium-238 atoms originally present. This number can be written:

$$\text{atoms of } ^{92}\text{U originally present} = \text{atoms of } ^{238}\text{U now present} + \text{atoms of } ^{206}\text{Pb now present}$$
If we assume that we now have 1,000 uranium-238 atoms, we can solve for the number of lead atoms:

$$0.115 = \frac{\text{atoms of } ^{206}_{82}\text{Pb now present}}{\text{atoms of } ^{238}_{92}\text{U now present}} = \frac{\text{atoms of } ^{206}_{82}\text{Pb now present}}{1000}$$

atoms of $^{206}_{82}$Pb now present $= 0.115 \times 1000 = 115$

Now we can compute the number of uranium-238 atoms originally present:

$$\text{atoms of } ^{238}_{92}\text{U originally present} = \text{atoms of } ^{238}_{92}\text{U now present} + \text{atoms of } ^{206}_{82}\text{Pb now present}$$

$$\text{atoms of } ^{238}_{92}\text{U originally present} = 1000 + 115 = 1115$$

Now we have:

$$N = 1000 \quad \text{and} \quad N_0 = 1115$$

Now we have all the numbers we need to plug into the rate equation to solve for $t$:

$$t = -\frac{1}{k} \ln \left( \frac{N}{N_0} \right) = -\left( \frac{4.5 \times 10^9 \text{ yr}}{\ln 2} \right) \ln \left( \frac{1000}{1115} \right) = 7.1 \times 10^8 \text{ yr}$$

- **Radiotracers in Medicine**: Radioactive nuclides have proven to be quite valuable in biological research and in medicine. Here are some examples:
  - **Iodine-131**: Iodine when ingested will concentrate in the thyroid gland. When a patient drinks a solution of sodium iodide containing small amounts of iodine-131, the uptake of iodine by the thyroid gland can be monitored by imaging the radiation produced by decay of the iodine-131, as seen in Figure 18.8:
• **Thallium-201:** When thallium is ingested, it concentrates in healthy heart tissue. Thallium-201 thus will form an image in healthy heart tissue and show by its relative absence those parts of the heart damaged by a heart attack.

• **Technicium-99m:** Technecium-99m behaves similarly to thallium-201 and can also be used to help assess damage to the heart by a heart attack.

• **Other Medically Useful Nuclides:** Table 18.5 lists some other radioactive nuclides useful as diagnostic tracers in medicine.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Half-Life</th>
<th>Area of the Body Studied</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{131}$I</td>
<td>8.1 days</td>
<td>Thyroid</td>
</tr>
<tr>
<td>$^{59}$Fe</td>
<td>45.1 days</td>
<td>Red blood cells</td>
</tr>
<tr>
<td>$^{99}$Mo</td>
<td>67 hours</td>
<td>Metabolism</td>
</tr>
<tr>
<td>$^{32}$P</td>
<td>14.3 days</td>
<td>Eyes, liver, tumors</td>
</tr>
<tr>
<td>$^{51}$Cr</td>
<td>27.8 days</td>
<td>Red blood cells</td>
</tr>
<tr>
<td>$^{87}$Sr</td>
<td>2.8 hours</td>
<td>Bones</td>
</tr>
<tr>
<td>$^{99m}$Tc</td>
<td>6.0 hours</td>
<td>Heart, bones, liver, and lungs</td>
</tr>
<tr>
<td>$^{133}$Xe</td>
<td>5.3 days</td>
<td>Lungs</td>
</tr>
<tr>
<td>$^{24}$Na</td>
<td>14.8 hours</td>
<td>Circulatory system</td>
</tr>
</tbody>
</table>

• **Characteristics of a Useful Radiotracer:**

  It must be chemically non-toxic.
It needs to concentrate in the tissue of interest and not in surrounding tissue.

Its decay must produce a detectable signal.

The radiation produced by its decay must not cause the organism undue harm.

The nuclides produced by its decay must be chemically non-toxic.