Nuclear Chemistry: Radioactivity, Decay, Dating and Other Hazards

I. Radioactive Isotopes and Nuclear Equations

Atoms are composed of three main subatomic particles: protons, neutrons and electrons. Protons and neutrons are found in the nucleus of an atom. The total number of protons and neutrons determines an atom’s mass. The number of protons defines the element.

Some nuclei are unstable, so they decompose (or "decay") over time, spontaneously emitting particles and/or energy. Such emissions are called radioactivity (or radioactive decay) and such unstable atoms are referred to as radioactive isotopes or radioactive nuclides. Different isotopes are identified by their element name or chemical symbol and their mass number. For example, uranium-235 (U-235) and uranium-238 (U-238) are two different isotopes of the element uranium, and carbon-12 (C-12) and carbon-14 (C-14) are isotopes of the element carbon.

Some isotopes can also be induced to decay as a result of bombardment by high-energy particles (e.g. neutrons, electrons, and other nuclei). These kinds of nuclear changes are called nuclear transmutation.

Both radioactive decay and nuclear transmutation are examples of nuclear reactions.

Atomic Notation: Shorthand for keeping track of protons and neutrons in the nucleus

\[
\text{mass number} = A \\
\text{atomic number} = Z \\
E = \text{Element symbol}
\]

atomic number: number of protons (\(p^+\)) = number of electrons (\(e^-\)) in a neutral atom.

mass number: whole number sum of protons (\(p^+\)) and neutrons (\(n\)) in an atom’s nucleus. Different isotopes of an element will have different mass numbers.

Some common particles have the following atomic notation: proton = \(1^1H\) neutron = \(0^1n\) electron = \(-1^0e\)

Exercise 1: Complete the following table:

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Mass Number</th>
<th># of Protons</th>
<th># of Neutrons</th>
<th># of Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xenon - 143</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{99}\text{Mo})</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thorium - 229</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Modes of Decay

There are five different ways in which naturally occurring radioactive nuclei decay. Note that in emission reactions, often called decay reactions, the nuclear particle is a product. In the capture reaction, the nuclear particle is a reactant. A reactant isotope is called the parent nuclide, while a product isotope is called the daughter nuclide.
alpha (α) emission (or decay): a helium nucleus, 42α or 6He, is emitted. In alpha decay reactions, the parent and daughter are different elements with different mass numbers.

\[ ^{238}_{92}\text{U} \rightarrow ^{4}_2\alpha + ^{234}_{90}\text{Th} \]

beta (β) emission (or decay): an electron, 0β or 0e, is emitted when a neutron inside an atom decays to produce a proton and an electron. In this case, the parent and daughter are different elements but the mass remains the same.

\[ ^{234}_{90}\text{Th} \rightarrow ^{0}_0\beta + ^{234}_{91}\text{Pa} \]

gamma (γ) emission (or decay): high energy photons or gamma rays, 0γ, are emitted. This generally accompanies the emission of a particle.

\[ ^{99}_{43}\text{Tc} \rightarrow ^{99}_{43}\text{Tc} + ^{0}_0\gamma \]

positron (ε) emission (or decay): a positron, 0e, is emitted when a proton inside an atom decays to produce a neutron and a positron. In this type of radioactive decay, the parent and daughter are different elements but have the same mass.

\[ ^{22}_{11}\text{Na} \rightarrow ^{0}_1\text{e} + ^{22}_{10}\text{Ne} \]

electron capture: an electron in the 1s orbital "falls" into the nucleus, which fuses with a proton to form a neutron.

\[ ^{82}_{37}\text{Rb} + ^{0}_1\text{e} \rightarrow ^{82}_{36}\text{Kr} \]

A nuclear reaction can also be forced to occur by bombarding a radioactive isotope with another particle. This process of causing radioactivity is called nuclear transmutation. Nuclear transmutations can result in α-, β-, and γ-emissions as well as the production of protons, neutrons, and other isotopes:

\[ ^{235}_{92}\text{U} + ^{1}_0\text{n} \rightarrow ^{141}_{56}\text{Ba} + ^{92}_{36}\text{Kr} + 3^1_0\text{n} \]

Balancing Nuclear Equations

This differs from balancing general chemical equations because instead of balancing elements (or atoms) present, mass numbers (protons + neutrons) and atomic numbers are balanced.

For example:

\[ ^{222}_{86}\text{Rn} \rightarrow ^{218}_{84}\text{Po} + ^{4}_2\alpha \]

where the mass numbers are equal to 222, and the atomic numbers are equal to 86.

Exercise 1: Identify the unknown element in each to complete the following nuclear equations:

a. What element is formed when plutonium-239 is struck by an alpha particle?

\[ ^{239}_{94}\text{Pu} + ^{4}_2\alpha \rightarrow ^{1}_0\text{n} + \underline{\text{______}} \]

b. Uranium-235 undergoes nuclear fission when it collides with a neutron:

\[ ^{235}_{92}\text{U} + ^{1}_0\text{n} \rightarrow ^{90}_{38}\text{Sr} + 4^1_0\text{n} + \underline{\text{______}} \]
Exercise 2: Write complete nuclear equations for the following processes:
   a. Neptunium-237 is the daughter nuclide when a radioactive isotope undergoes alpha decay.

   b. Platinum-194 is the daughter nuclide when a radioactive isotope undergoes beta decay.

Exercise 3: Actinium-227 is produced during a radioactive decay series. This nuclide is also unstable and several successive decay reactions occur before a stable nuclide, Pb-207, is eventually formed. Write balanced nuclear equations for the decay of actinium-227 to lead-207 in eight steps.
   a. Step 1: Actinium-227 decays by alpha emission. (Actinium has the element symbol Ac).

   b. Step 2: The daughter product in part a decays by beta and gamma emission.

   c. Step 3: The daughter product in part b decays by alpha and gamma emissions.

   d. Step 4: The daughter product in part c decays by alpha and gamma emissions.

   e. Step 5: The daughter product in part d decays by alpha emission.

   f. Step 6: The daughter product in part e decays by beta emission.

   g. Step 7: The daughter product in part f decays by alpha and gamma emissions.

   h. Step 8: The daughter product in part g decays by beta emission.

The final stable isotope is lead-207.
II. Half-Life and Radioactive Decay Problems

Table 1. Half-lives for U-238 Decay Series

<table>
<thead>
<tr>
<th>Type of Radiation</th>
<th>Nuclide</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>uranium-238</td>
<td>4.47 billion years</td>
</tr>
<tr>
<td>β</td>
<td>thorium-234</td>
<td>241 days</td>
</tr>
<tr>
<td>β</td>
<td>protactinium-234m</td>
<td>1.17 minutes</td>
</tr>
<tr>
<td>α</td>
<td>uranium-234</td>
<td>245,000 years</td>
</tr>
<tr>
<td>α</td>
<td>thorium-230</td>
<td>8000 years</td>
</tr>
<tr>
<td>α</td>
<td>radium-226</td>
<td>1600 years</td>
</tr>
<tr>
<td>α</td>
<td>radon-222</td>
<td>3.823 days</td>
</tr>
<tr>
<td>α</td>
<td>polonium-218</td>
<td>3.05 minutes</td>
</tr>
<tr>
<td>β</td>
<td>lead-214</td>
<td>26.8 minutes</td>
</tr>
<tr>
<td>β</td>
<td>bismuth-214</td>
<td>19.7 minutes</td>
</tr>
<tr>
<td>β</td>
<td>polonium-214</td>
<td>0.000164 seconds</td>
</tr>
<tr>
<td>α</td>
<td>lead-210</td>
<td>22.3 years</td>
</tr>
<tr>
<td>β</td>
<td>bismuth-210</td>
<td>5.01 days</td>
</tr>
<tr>
<td>β</td>
<td>polonium-210</td>
<td>136.4 days</td>
</tr>
<tr>
<td>α</td>
<td>lead-206</td>
<td>stable</td>
</tr>
</tbody>
</table>

Radioactive decay is a first-order rate process; thus, radioactive processes obey the first-order integrated rate law:

$$\ln \left( \frac{A_t}{A_0} \right) = -kt$$

where \( A_0 \) = initial activity or amount of substance; \( A_t \) = activity or amount of substance after a certain time; \( k \) = rate constant; and \( t \) = time.

All radioactive nuclides also have a characteristic half-life, \( t_{1/2} \), which is the time required for half the amount of a radioactive sample to decay. For first-order reactions, the half-life is related to the rate constant, \( k \), by the following equation:

$$t_{1/2} = \frac{0.693}{k}$$

Table 1 (left) indicates the half-lives and decay processes for all the radioactive isotopes in the decay series for Uranium-238. Use the information provided in the table and the equations above to answer the following questions:

Exercise 1: a. What is the half-life for radium-226? _______

b. How many half-lives have passed for radium-226 after 9,600 years? _____ half-lives (HL)

c. How much of a 885 mg sample of radium-226 would remain after 9,600 years?

d. What is the value of the rate constant, \( k \), for radium-226? Include units for \( k \)!

e. How much of a 422 mg sample of radium-226 would remain after 3,800 years?

f. How much time would it take for 755 mg of radium-226 to decay to 167 mg?
### III. Applications of Radioactive Isotopes

The half-lives of different radioactive nuclides range from fractions of a second to billions of years. Examples of parent-daughter pairs, their decay processes, half-lives, and applications are listed below.

<table>
<thead>
<tr>
<th>Parent/Daughter</th>
<th>Decay Process</th>
<th>Half-life</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strontium-90 / Yttrium-90</td>
<td>β emission</td>
<td>28.8 years</td>
<td>Industrial applications and treatment for eye and skin diseases</td>
</tr>
<tr>
<td>Iodine-123 / Tellerium-123</td>
<td>e⁻ capture and γ emission</td>
<td>13 hours</td>
<td>Thyroid imaging</td>
</tr>
<tr>
<td>Iodine-131 / Xenon-131</td>
<td>β emission</td>
<td>8 days</td>
<td>Thyroid treatment</td>
</tr>
<tr>
<td>Technetium-99m (excited) / Technetium-99</td>
<td>γ emission</td>
<td>6 hours</td>
<td>Bone scans</td>
</tr>
<tr>
<td>Phosphorus-32 / Sulfur-32</td>
<td>β emission</td>
<td>14.28 days</td>
<td>Leukemia Therapy; tracers used in DNA sequencing</td>
</tr>
<tr>
<td>Americium-241 / Neptunium-237</td>
<td>β and γ emissions</td>
<td>432 years</td>
<td>Smoke detectors</td>
</tr>
<tr>
<td>Plutonium-239 / Uranium-235</td>
<td>α and γ emissions</td>
<td>24,400 years</td>
<td>Nuclear reactors</td>
</tr>
<tr>
<td>Uranium-235 / Pb-207</td>
<td>series of α and γ emissions</td>
<td>713 million years</td>
<td>Archeological Dating</td>
</tr>
<tr>
<td>Potassium-40 / Argon-40</td>
<td>electron capture</td>
<td>1.25 billion years</td>
<td></td>
</tr>
<tr>
<td>Carbon-14 / Nitrogen-14</td>
<td>β emission</td>
<td>5730 years</td>
<td></td>
</tr>
<tr>
<td>Rubidium-87 / Strontium-87</td>
<td>β emission</td>
<td>50 billion years</td>
<td></td>
</tr>
<tr>
<td>Uranium-238 / Lead-206</td>
<td>series of 14 α and β emissions</td>
<td>4.50 billion years</td>
<td></td>
</tr>
</tbody>
</table>

#### Uses for Radioactive Isotopes

Medical professionals often use radioactive isotopes to visualize certain parts of the body. One such chemical is a phosphate compound of Technetium-99m (Tc-99m).

1. The half-life for Technetium-99m is ________________. [Use Table 2]

2. If one is having such a bone scan done, the Tc-99m compound is administered intravenously, and **the scan is done three hours later**.

   How many half-lives (HL) have passed when the scan is done? ____________ HL

3. Use the information from questions 1 and 2 to calculate what percentage of the Tc-99m remains in the body after the scan is done. Use three significant figures for the percentage and show your work!

    __________%  

Smoke detectors also take advantage of radioactivity by using Americium-241, an artificially produced radioactive isotope that emits alpha particles and low energy gamma rays.

4. The half-life for Americium-241 is ________________. [Use Table 2]

5. How many half-lives have passed after 100 years? ____________ HL (use three significant figures)

6. Use the information from questions 4 and 5 to calculate what percentage of the Americium-241 remains after 100 years. Use three significant figures for the percentage and show your work!

    __________%
7. A smoke detector requires about 0.3 micrograms of Americium-241 to work properly. If the smoke detector originally contains 0.5 microgram of Americium-241, does it contain enough radioactive material to function properly after 100 years? Explain your answer.

IV. Radioactive Decay and Dating

Geologists, archaeologists, paleontologists and biologists also use certain radioisotopes to date rocks, fossils, and artifacts. Notice the difference in half-lives for isotopes used in archaeological dating versus isotopes used for medicinal purposes (see Table 2 on page 5). Explain why medical isotopes have considerably shorter half-lives.

Radiocarbon Dating

Click on the link for Radiocarbon dating:
http://www.sciencecourseware.com/VirtualDating/files/RC0/RC_0.html

Answer the questions on the first 5 pages on the tutorial. Notice that many of the pages have interactive tools to help you in answering the questions. Complete all the questions, including those on the “Applying the Radiocarbon Decay Curve” (page 5) page. The questions below are found on the indicated pages of the tutorial. Stop when you get to the “What about AD, BC, BCE and BP ages” page.

1. (page 3) The C-14 method cannot be used to confirm the age of a silver goblet from the 1500’s. Explain.

2. (page 5) The smallest C-14 activity that can be measured is about 0.2%. If C-14 is used to date an object, the object must have died within how many years?