Chapter 20 Nuclear Chemistry

1. Nuclear Reactions

Nuclear reactions - reactions that change the nucleus.

Nuclear reactions involve the particles located in the nucleus of the atom:

nucleons: ____________________________________________.

An atom is characterized by its atomic number, Z and its mass number, A.

Mass # (A) - ______

Atomic # (Z) - ______

If we change the # of (p), we have a different __________

If we change the number of (n), we have a different __________

Nuclides – the nucleus of a specific isotope of an element.

A radioactive nuclide is known as a ______________________

2. Nuclear Reactions and Radioactivity

To be radioactive means that the nuclei spontaneously emit radiation.

Why Radioactivity Occurs: Stable and Unstable Isotopes

1. Every element has at least one radioisotope (radioactive isotope).
2. Most have stable isotopes, but some don’t have any.
3. Radioactivity occurs as a byproduct of an unstable nucleus trying to become more stable!

Common Reasons for instability

a) ________________________________

For all elements above bismuth (#83), all isotopes are radioactive.

b) ________________________________
Even vs Odd numbers of protons and neutrons

**Stability is favored** by _______ numbers of neutron and _______ numbers of protons

264 non-radioactive isotopes

<table>
<thead>
<tr>
<th></th>
<th>Protons</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>even</td>
<td>odd</td>
</tr>
<tr>
<td>neutrons</td>
<td>even</td>
<td>odd</td>
</tr>
</tbody>
</table>

**Relative amounts of protons and neutrons**

NUCLEAR STABILITY

An isotope that is off the belt of stability can use four nuclear reactions to get to it:

1. α
2. β
3. positron emission
4. electron capture

The most stable isotopes of lighter elements (up to Ca-20) have a neutron to proton ratio of ~1:1 (or just one more neutron than proton).

The ratio of neutrons to protons increases to almost 1.5 to 1 for heavier elements.
3. Nuclear Decay and Types of Radiation

The Three Most Common Types:

a. alpha (α), beta (β), gamma (γ)

The radioactive source in the shielded box emits radiation, which passes between two electrically charged plates.

- Alpha radiation is deflected towards the negative plate.
- Beta radiation is deflected towards the positive plate.
- Gamma radiation passes right through.

Radiation Types – A Closer Look

**Alpha (α) Radiation –**

1. Common in __________ radio-isotopes. (those that have too large of a nucleus to be stable)
2. A stream of particles that consist: ____________________________
3. ________charged
4. Represented as: ________________.
5. Travels at ? % of the speed of light: _____
6. penetrating power (can be stopped by a piece of paper or 0.03 mm H₂O.)
7. damage potential (high ionizing power)
**Balancing Nuclear Reactions**

1. The sum of the mass numbers must be equal on both sides of the reaction.
2. The sum of the atomic numbers must be equal on both sides of the reaction.

Let's look at the decay of uranium-238 (aka U-238)

\[ ^{238}_{92} \text{U} \rightarrow ^{4}_{2} \text{He} + ^{234}_{90} \text{Th} \]

**LP#1.** What product results from alpha emission by radon-222?

\[ ^{222}_{86} \text{Rn} \rightarrow ^{4}_{2} \text{He} + \_\_\_\_\_\_\_\_\_\_\_\_ \]

**LP#2.** What isotope is converted into radon-222 by alpha emission?

\_\_\_\_\_\_\_\_\_\_\_\_ \rightarrow ^{222}_{86} \text{Rn} + ^{4}_{2} \text{He} \]

**Beta (β) Radiation -**

1. Occurs when the # neutrons is too ______
2. A neutron is converted to a proton plus an electron.

\[ ^{1}_{0} \text{n} \rightarrow ^{1}_{1} \text{p} + ^{0}_{-1} \text{e} \]
3. The electron is not welcome in the nucleus and is ejected as a beta particle.
4. Represented as ________________

   There is no such thing as a −1 number of protons. It is used as a reaction balancing technique to show that the number of protons is changing by 1.
5. Travels at ? % of the speed of light: ______
6. Penetrating Power (Can be stopped by heavy clothing or 2 mm H₂O.)
7. damage potential

Example: \[ ^{131}_{53} \text{I} \rightarrow ^{131}_{54} \text{Xe} + ^{0}_{-1} \text{e} \]

**LP#3.** Carbon-14, a beta emitter, is a rare isotope used in dating archaeological artifacts. Write a nuclear equation for the decay of carbon-14.
**Gamma (γ) Radiation**

1. Electromagnetic radiation of very high energy and short wavelength.
2. Stream of high energy photons or light.
3. Represented by: __________
4. Almost always accompanies α and β emission.
5. mechanism for excited nuclei to: ___________________
6. gamma emission is often not shown in nuclear equations.
7. Penetrating Power. (Can be stopped by 10 cm of H₂O.)
8. _______ damage potential
9. Travels at: _____________________

Example:
\[ ^{60}_{27}\text{Co} \rightarrow ^{60}_{28}\text{Ni} + ^{0}_{-1}\text{e} + ^{0}_{0}\gamma \]

**Metastable nucleus**: Gamma emission usually occurs very quickly after radioactive decay. Sometimes the excited state can have a significant lifetime before gamma emission.

*A metastable nucleus is an excited nucleus with a lifetime of at least 1 nanosecond.*

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

**Positron Emission**

1. Occurs when the # neutrons is too ______
2. A proton is converted to a neutron plus a positron.
   \[ ^{1}_{1}\text{P} \rightarrow ^{0}_{0}\text{n} + ^{+1}_{0}\text{e} \quad \text{(CHARGE OF PROTON IS EJECTED)} \]
3. **Positron** - a particle with the same mass as an electron but opposite charge
4. Represented by ______________________
5. The positron is not welcome in the nucleus and is ejected.
6. Positrons are very short-lived particles.

Positrons are **antimatter**. They are annihilated as soon as they encounter electrons. When they collide, they form 2 gamma photons that carry away the energy.

Example: Potassium-40 emits a positron when it decays.
\[ ^{40}_{19}\text{K} \rightarrow ^{40}_{18}\text{Ar} + ^{0}_{+1}\text{e} \]
LP#4. Write a nuclear equation for positron emission from calcium-38

**Positron Emission Tomography (PET)**

PET scanning is a nuclear medicine functional imaging technique that is used to observe metabolic processes in the body. The system detects pairs of gamma rays emitted indirectly by a positron-emitting radionuclide (tracer), which is introduced into the body on a biologically active molecule. Three-dimensional images of tracer concentration within the body are then constructed by computer analysis.

Radionuclides used in PET scanning are typically isotopes with short half-lives such as carbon-11 (~20 min), nitrogen-13 (~10 min), oxygen-15 (~2 min), fluorine-18 (~110 min), gallium-68 (~67 min), zirconium-89 (~78.41 hours), or rubidium-82 (~1.27 min). These radionuclides are incorporated either into compounds normally used by the body such as glucose (or glucose analogues), water, or ammonia, or into molecules that bind to receptors or other sites of drug action.

**Electron Capture**

1. Occurs when the # neutrons is too _______
2. \( ^1_1\text{p} + ^0_{-1}\text{e} \rightarrow ^0_0\text{n} \) (CHARGE OF PROTON IS NEUTRALIZED)
3. A proton in the nucleus captures an inner-shell electron which is converted into a neutron. (OPPOSITE OF BETA EMISSION)
4. Only natural decay process with 2 reactants!

Example: Mercury-197 is capable of electron capture.

\[ ^{197}_{80}\text{Hg} + ^0_{-1}\text{e} \rightarrow ^{197}_{79}\text{Au} \]

LP#5. Write a nuclear equation for electron capture by zinc-62.
**Radioactive Decay Series**

Sometimes, the product of radioactive decay is still unstable. In this case, additional decay steps will follow until a stable nucleus is formed. A well documented radioactive decay series is that of uranium-238.

![Diagram of 238U Decay]

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**TABLE 20.1. Modes of Radioactive Decay**

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Process</th>
<th>A</th>
<th>Change in Z</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>Parent nuclide → Daughter nuclide + α particle</td>
<td>−4</td>
<td>Increase</td>
<td>$^{238}\text{U} \rightarrow ^{234}\text{Th} + \alpha$</td>
</tr>
<tr>
<td>β</td>
<td>Parent nuclide → Daughter nuclide + β particle</td>
<td>0</td>
<td>Decrease</td>
<td>$^{218}\text{Po} \rightarrow ^{214}\text{Pb} + \beta$</td>
</tr>
<tr>
<td>γ</td>
<td>Excited nuclide → Stable nuclide + γ ray</td>
<td>0</td>
<td>None</td>
<td>$^{90}\text{Tc} \rightarrow ^{90}\text{Tc} + \gamma$</td>
</tr>
<tr>
<td>Proton</td>
<td>Parent nuclide → Daughter nuclide + Proton</td>
<td>0</td>
<td>Increase</td>
<td>$^{208}\text{Tl} \rightarrow ^{208}\text{Tl} + \alpha$</td>
</tr>
<tr>
<td>Electron capture</td>
<td>Parent nuclide → Daughter nuclide + Electron</td>
<td>0</td>
<td>Increase</td>
<td>$^{208}\text{Po} \rightarrow ^{208}\text{Po} + e^-$</td>
</tr>
</tbody>
</table>

* Neutron-to-proton ratio © 2017 Pearson Education, Inc.
4. Nuclear Transmutation & Bombardment Reactions

Many radioactive elements are made by humans.

**Nuclear transmutation** - the change of one element into another. This occurs in natural decay processes, but the term more typically describes bombardment of an atom with a high-energy particle (alpha, beta, n, etc.).

This typically takes place in a __________________________ .

Example: Rutherford used alpha particles given off from a natural decay process to bombard Nitrogen-14.

\[
\begin{align*}
{}^{14}_7\text{N} & + {}^4_2\text{He} \rightarrow \text{______________} \\
\text{He} & \text{ obtained a proton and oxygen-17 (never before observed)} \\
\text{(FIRST MAN-MADE ISOTOPE)}
\end{align*}
\]

**Trans-uranium Elements (All Man-Made Elements)**

These are elements with atomic numbers greater than uranium (Z=92). Uranium has the largest naturally occurring atomic number. All trans-uranium elements have been produced by bombardment reactions. Example: If we bombard U-238 with alpha particles, a neutron plus another nucleus are formed. Write the reaction.

Plutonium is a man-made element.

(The symbol is in outline only for man-made elements on some periodic tables)

(Elements with molar mass in () have only radioactive isotopes with usually the mass # of the longest lived isotope given.)

5. Detection & Biological Effects of Radiation

**Ionizing Radiation**

Alpha, beta, gamma, x-rays and high energy neutrons are all forms of ionizing radiation – they remove one or more electrons from molecules.

In bio systems (mostly water) the reaction is:

\[
\begin{align*}
\text{Radiation} & + \text{H}_2\text{O} \rightarrow \text{______________} \\
\text{Then} & \\
\text{H}_2\text{O} & + \text{H}_2\text{O}^+ \rightarrow \text{______________}
\end{align*}
\]
Free radicals:
  # contain an unpaired electron # attack bio-molecules
  # are very reactive (cause cancer & genetic problems)

**X-rays** penetrate the deepest and can cause significant damage.

Tissues **most damaged** are rapidly reproducing like:

---

**Variation in Radiation Effects and Intensity Vs Distance (not in text)**

Effects of ionizing radiation on the human body vary with:

1. __________________________
   a. The intensity of the radiation decreases with the square of the distance.
      If you move twice as far away, the radiation level falls to \(1/4\).
      If you move 4 times as far away, the radiation level falls to \(1/16\)th.
      \[
      \frac{I_1}{I_2} = \frac{d_2^2}{d_1^2}
      \]

2. __________________________

3. ____________ inside or outside the body
   a. \(\alpha\) and \(\beta\) are not very dangerous outside the body because they can be
      stopped by several layers of clothing.
   b. \(\alpha\) and \(\beta\) are much more dangerous when placed inside the body because
      they are taken up by surrounding tissue.
   c. alpha emitters are almost never used internally in medicine.

4. __________________________can reduce exposure.

**LP#6.** A beta emitting source gives 250. units of radiation at a distance of 4.0m. At
what distance does the radiation drop to one tenth it’s original value?
6. Rate of Decay

Order of Kinetics

ALL nuclear disintegration reactions follow ________________ kinetics.

Reminder: Relationship between \( t_{\frac{1}{2}} \) and \( k \)

Integrated Rate Law (Refer back to kinetics chapter)

Previously: \( \ln \left( \frac{[A]_t}{[A]_0} \right) = -kt \)

Since this is a ratio and the concentration is proportional to the absolute amount of radioactive material present or the decay rate:

\[
\ln \left( \frac{N_t}{N_o} \right) = -kt
\]

. \( N_o \) = number of radioactive nuclei originally present; \( N_t \) = number remaining at time \( t \)

\( OR \)

\[
\ln \left( \frac{\text{rate}_t}{\text{rate}_o} \right) = -kt
\]

where rate = rate of decay in any units such as discintegrations per minute (dpm) or counts per minute (cpm)

Raising both sides to the power of \( e \):

Previously: \( \frac{[A]_t}{[A]_0} = e^{-kt} \)

Now becomes:

**How much Remains after a given time?**

Rearranging previous equations:

\[ N_t = N_o \left( e^{-kt} \right) \]

\[ \text{Rate}_t = \text{rate}_o \left( e^{-kt} \right) \]
Radioisotope iodine-131, used to treat hyperthyroidism, has a half-life of 8.0 days. If a patient is given a dose of 8.2 μg of this isotope, what mass remains after 28 days?

Start by calculating \( k \) from the half-life.

\[
k = \frac{0.693}{t_{\frac{1}{2}}} = \frac{0.693}{8.0} = ______________
\]

\[
N_t = N_o e^{-kt} = ______________
\]

How much did you start with?

To figure out how much radioactive material was present at the beginning, based on current amounts, you need to do the reverse process.

\[
N_0 = \frac{N_t}{e^{-kt}} \quad \text{OR} \quad \text{rate}_0 = \text{rate}_t / e^{-kt}
\]

Radiocarbon Dating

It is based on the fact that there is a nearly constant amount of ______ in our atmosphere. It comes from ___ ____________ (from outer space) containing neutrons that react with ______ in the atmosphere.

This is only a small fraction of the carbon in the atmosphere.

Relative abundances of carbon isotopes in our atmosphere are:

- C-12 (stable)  
- C-13 (stable)  
- C-14 (radioactive) 0.0000000001%

The C-14 is incorporated into compounds such as \( \text{CO}_2 \). This gets photosynthesized into plant material, then eaten by animals. The C-14 is constantly decaying by beta emission.

An equilibrium is established as long as the plant or animal ________  
(The C-14 is being replaced at the same rate it is going away.)

After death: C-14 levels drop.
**LP#8.** If live plant material has C-14 at a level that generates 15.3 dpm (per g C)

How old is an artifact if the measured activity of C-14 is 11.8 dpm?

The half-life of C-14 is 5715 yrs.

Problems asking for the amount of time are better solved with the

form of the equation: \[ \ln \left( \frac{rate_t}{rate_0} \right) = -kt \]

Rearranging, \[ t = \ln \left( \frac{rate_t}{rate_0} \right) \]

\[ ratae_t = \]

\[ rate_0 \]

\[ k = \]

\[ t = \]

Limitations:

- Good for > ______________
  (less and we don’t see enough of a change)

- Good for < ______________
  (more and there isn’t enough C-14 left to measure accurately)

**Dating Older Items**

Several techniques exist.

One of the most dependable relies on the decomposition of U-238 to Pb 206 in volcanic rock.

There are many decay steps involved, but the overall half-life is $4.5 \times 10^9$ years.

It assumes that there was no Pb-206 in the rock at the time it formed.

All of the Pb was originally U at time=0

Starting **MOLES** of U would be the sum of the **MOLES** of Pb & U currently present.