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) - _______

This is the most common isotope of carbon.

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.

**Discovery and Nature of Radioactivity**

*Antoine Henri Becquerel*

1. Radioactivity was first discovered by the French Physicist in 1896.
2. He was studying phosphorescence.
3. Placed crystal of uranium on wrapped photographic plate.
4. The uranium exposed the film through the paper.
5. Called them ________________
**Marie Sklodowska Curie**

She and husband Pierre studied this phenomenon. She came up with the name radioactivity. Discovered 2 more radioactive elements: ___________________________
Earned 1903 Nobel Prize in Physics for work with Pierre and Henri. Earned 1911 Nobel Prize in Chemistry for discovery of 2 new elements

**Earnest Rutherford**

Discovered two separate types of radiation ___________________________
His student (Chadwick) soon afterwards discovered a 3rd ___________

**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) ___________________________

b1) 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>
b2) Relative amounts of protons and neutrons

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)

\[
\begin{align*}
238\,^92\text{U} & \rightarrow 4\,^2\text{He} + 234\,^{90}\text{Th} \\
\end{align*}
\]

**LP#1.** What product results from alpha emission by radon-222?
\[
\begin{align*}
\frac{222}{86}\text{Rn} & \rightarrow 4\,^2\text{He} + \text{__________} \\
\end{align*}
\]

**LP#2.** What isotope is converted into radon-222 by alpha emission?
\[
\begin{align*}
\text{__________} & \rightarrow \frac{222}{86}\text{Rn} + \frac{4}{2}\text{He} \\
\end{align*}
\]

**Beta (β) Radiation -**
1. Occurs when the # neutrons is too ______
2. A neutron is converted to a proton plus an electron.
\[
\begin{align*}
_0^1\text{n} & \rightarrow _1^1\text{p} + _{-1}^0\text{e} \\
\end{align*}
\]
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: $^{131}_{53}\text{I} \rightarrow ^{131}_{54}\text{Xe} + ^{0}_{-1}e$

**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:

$^{60}_{27}\text{Co} \rightarrow ^{60}_{28}\text{Ni} + ^{0}_{-1}e + ^{0}_{0}\gamma$

**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.
   \[ _1^1p \rightarrow _0^1n + _{+1}^0e \] (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 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.

\[ ^{40}_{19}K \rightarrow ^{40}_{18}Ar + ^0_{+1}e \]

**LP#4.** Write a nuclear equation for positron emission from calcium-38

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**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. \( \frac{1}{1}p + \frac{0}{-1}e \rightarrow \frac{1}{0}n \) (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.

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

**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.
### TABLE 20.1 Modes of Radioactive Decay

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Process</th>
<th>Change in:</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>Parent nuclide → Daughter nuclide + α particle</td>
<td>A -4, Z -2, N/Z² Increase</td>
<td>$^{228}\text{U}<em>{92} \rightarrow ^{234}\text{Th}</em>{90} + ^{4}\text{He}_2$</td>
</tr>
<tr>
<td>β</td>
<td>Parent nuclide → Daughter nuclide + β particle</td>
<td>A 0, Z +1, N/Z² Decrease</td>
<td>$^{228}\text{Rn}<em>{86} \rightarrow ^{228}\text{Ac}</em>{88} + ^{2}\text{e}_1$</td>
</tr>
<tr>
<td>γ</td>
<td>Excited nuclide → Stable nuclide + γ photon</td>
<td>A 0, Z 0, N/Z² None</td>
<td>$^{99}\text{Tc}<em>{43} \rightarrow ^{99}\text{Tc}</em>{43} + ^{0}\gamma_1$</td>
</tr>
<tr>
<td>Positron emission</td>
<td>Parent nuclide → Daughter nuclide + β particle</td>
<td>A 0, Z -1, N/Z² Increase</td>
<td>$^{30}\text{P}<em>{15} \rightarrow ^{28}\text{Si}</em>{14} + ^{2}\text{e}_1$</td>
</tr>
<tr>
<td>Electron capture</td>
<td>Parent nuclide → Daughter nuclide + β particle</td>
<td>A 0, Z -1, N/Z² Increase</td>
<td>$^{46}\text{Cu}_{29} + ^{2}\text{e}<em>1 \rightarrow ^{44}\text{Tc}</em>{22}$</td>
</tr>
</tbody>
</table>

* Neutron-to-proton ratio
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**LP#6.** Predict whether Mg-28 is more likely to decay via beta decay or positron emission.

**LP#7.** Predict whether Mg-22 is more likely to decay via beta decay or positron emission.
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.

\[
^{14}_7 \text{N} + ^4_2 \text{He} \rightarrow \text{______________}
\]

He obtained a proton and oxygen-17 (never before observed)

(FIRST MAN-MADE ISOTOPE)

Lighter and heavier elements are less stable than mid-mass elements near iron-56.

1. Typically, **heavy** nuclei gain stability and release energy if they fragment to yield mid-mass elements. Known as ________________

2. Typically, **light** nuclei can gain stability and release energy if they fuse together. Known as ___________________________
**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.)

**Preparation of Cobalt-60**
Cobalt-60 is a man-made isotope used for radiation therapy of cancer patients.

1. Stable Fe-58 is bombarded with a neutron to form __?

2. Unstable Fe-59 decays by beta emission to from the stable product ___.

3. Stable Co-59 is then bombarded with a neutron to form?

Cobalt-60 decays by beta (and gamma) emission (t½ = 5.3 years). These beta
particles are then aimed at cancerous tumors.

Tumors are more susceptible to radiation because they are

What nuclei remains after beta and gamma decay of Co-60?
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:

\[
\text{Radiation} + \text{H}_2\text{O} \rightarrow \text{___________}
\]

Then

\[
\text{H}_2\text{O} + \text{H}_2\text{O}^+ \rightarrow \text{___________}
\]

Free radicals:

- contain an unpaired electron
- are very reactive
- attack bio-molecules
  (cause cancer & genetic problems)

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

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

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**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.
   
   \[
   \frac{I_1}{I_2} = \frac{d_2^2}{d_1^2}
   \]
   
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#8. 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 __________ kinetic.

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:

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

. \( N_0 \) = 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 
disintegrations per minute (dpm) 
or counts per minute (cpm)

Raising both sides to the power of e:

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

Now becomes:
Half Life – First Order Kinetics

Radioactive decay is characterized by a half-life, \( t_{\frac{1}{2}} \):

1. Time required for the number of radioactive nuclei in a sample to drop to one-half of the initial value.
2. Each passage of a half-life causes the decay of one-half of whatever sample remains.
   100% x \( \frac{1}{2} \) = 50% left after 1 half life
   50% x \( \frac{1}{2} \) = 25% left after 2 half lives
   25% x \( \frac{1}{2} \) = 12.5% left after 3 half lives
3. The half-life is the same no matter what the size of the sample, the temperature, or any other external condition.

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

**How much Remains?**

Rearranging previous equations:

\[
N_t = N_0 \ (e^{-kt}) \quad \text{OR} \quad N_t = \frac{N_0}{(e^{-kt})}
\]

\[
\text{Rate}_t = \text{rate}_0(e^{-kt}) \quad \text{OR} \quad \text{rate}_t = \frac{\text{rate}_0}{(e^{-kt})}
\]

**LP#9.** 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 \( \mu g \) of this isotope, what mass remains after 28 days?

**Approach #1 (book approach)**

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

\[
k = \frac{0.693}{t_{\frac{1}{2}}} = \quad \text{__________________________}
\]

\[
N_t = N_0 \ e^{-kt} = \quad \text{__________________________}
\]

**Approach #2 (alternate approach)**

Start by calculating the number of half-lives elapsed.
**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.

\[ N_0 = N_t \times (2)^{\text{# half-lives}} \quad \text{OR} \quad \frac{\text{rate of decay}}{\text{rate of decay initial}} = (2)^{\text{# half-lives}} \]

**LP#10.** If 0.88 mCi of Tc-99m with a t-\( \frac{1}{2} \) of 6.0 hrs remains after 24 hrs, what dose was Prof. Nuss given for scanning by a gamma camera? (1 curie = 3.7x10^{10} decay events/sec)

Start by calculating the number of half-lives elapsed.

\[ \text{Amt at start} = \]

**Radiocarbon Dating**
Developed by: Professor Willard F. Libby et al
When/Where: in 1946 at the University of Chicago
Won Nobel Prize for his work in 1960.

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.