Chapter 20: Nuclear Chemistry

Nuclear Reactions vs. Chemical Reactions
There are some very distinct differences between a nuclear reaction and a chemical reaction.

- in a chemical reaction bonds break, atoms recombine, new bonds form
- in a nuclear reaction, the nucleus of an atom changes frequently resulting in its transformation into a different element
- the rate of a nuclear reaction is not affected by changes in T, P, or addition of a catalyst
- energy changes accompanying nuclear transformation are much greater than for chemical reactions

Overview of the Chapter
- nuclear reactions
  - how they differ from chemical reactions
  - types of radioactive decay
  - writing and balancing nuclear reactions
  - predicting products of nuclear transformations
- nuclear stability
  - neutron : proton ratio
- kinetics of nuclear decay
- nuclear fission vs. nuclear fusion reactions
- nuclear power

Review of Atomic Structure
atoms identified by: element symbol
- atomic number
- mass number

mass number: 
- protons and neutrons are found in the nucleus
- protons and neutrons have the same mass; are much heavier than electrons
- protons are + charged neutrons are neutral electrons are – charged
- nucleus is the center of mass and + charge in an atom

atomic number:
- 

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Isotopes and Nuclides

- Atoms with the same number of protons but different numbers of neutrons are *isotopes*.
  
  - same atomic number
  - different mass numbers
- the nucleus of a specific isotope is called a *nuclide*
- nuclides may be indefinitely stable, or radioactive
- radioactive nuclides undergo spontaneous decay and emission of radiation

Writing and Balancing Nuclear Equations

Because nuclear reactions typically involve a change in the identity of an element, they cannot be balanced in the same manner as a chemical reaction.

- focus on conservation of atomic # and mass #
- total number of nucleons remains the same

example:

transformation of curium-242

\[
{^{242}_{96}}\text{Cm} \rightarrow {^{4}_{2}}\text{He} + {^{238}_{94}}\text{Pu}
\]

Common Categories of Nuclear Reactions

- alpha emission
  
  emission of \(\alpha\) particle
- beta emission
  
  emission of \(\beta\) particle
- positron emission
  
  emission of \(\beta^+\) particle
- gamma emission (\(\gamma\))
  
  emission of high energy (short \(\lambda\)) photons
- electron capture
- spontaneous fission

Charge Characteristics of \(\alpha\), \(\beta\), and \(\gamma\) Radiation

- \(\alpha\) ray
- \(\beta\) ray
- \(\gamma\) ray
Alpha Emission
- $\alpha$ particles are positively charged
- helium nucleus, $^4_2\text{He}$ or $\alpha$
- emission of an $\alpha$ particle results in:
  - decrease in mass # by 4
  - decrease in atomic # by 2
- common emission reaction for heavy radioactive isotopes
- example:
  $$^{238}_{92}\text{U} \rightarrow ^{234}_{90}\text{Th} + ^4_2\text{He}$$

Beta Emission
- $\beta$ particles are negatively charged
- electron, $^0_{-1}\text{e}$ or $\beta$
- emission of an $\beta$ particle results in:
  - no change in mass #
  - increase in atomic # by 1
- $\beta$ emission occurs when a neutron decays to give a proton and an electron that is ejected from nucleus
  $$n \rightarrow p + e^-$$
- example:
  $$^{131}_{53}\text{I} \rightarrow ^{131}_{54}\text{Xe} + ^0_{-1}\text{e}$$

Positron Emission
- $\beta^+$ particles are positively charged
- opposite of an electron, $^0_1\text{e}$ or $\beta^+$
- emission of an $\beta^+$ particle results in:
  - no change in mass #
  - decrease in atomic # by 1
- $\beta^+$ emission occurs when a proton is converted to a neutron and a positron that is ejected from nucleus
  $$p \rightarrow n + \beta^+$$
- example:
  $$^{40}_{19}\text{K} \rightarrow ^{40}_{18}\text{Ar} + ^0_1\text{e}$$

Gamma Emission
- gamma radiation is high E, short $\lambda$ radiation
- $\gamma$ photons have no mass, no charge; $^0_0\gamma$
- $\gamma$ emission almost always accompanies other nuclear reactions
Electron Capture

- nucleus captures an inner shell e− resulting in the conversion of a proton to a neutron
  \[ p + e^- \rightarrow n \]
- electron capture results in:
  - no change in mass #
  - decrease in atomic # by 1
- example:
  \[ ^{197}_{80} \text{Hg} + ^{0}_{-1} \text{e} \rightarrow ^{197}_{79} \text{Au} \]

Summary of Nuclear Reactions

<table>
<thead>
<tr>
<th>Type of Decay</th>
<th>Radiation</th>
<th>Equivalent Process</th>
<th>Atomic Number</th>
<th>Mass Number</th>
<th>Resulting Nuclear Change</th>
<th>Usual Nuclear Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha emission (α)</td>
<td>3He</td>
<td>[ ^{0}<em>{-2} \text{He} \rightarrow ^{2}</em>{2} \alpha ]</td>
<td>-2</td>
<td>-4</td>
<td>Z &gt; 83</td>
<td></td>
</tr>
<tr>
<td>Beta emission (β)</td>
<td>3e</td>
<td>[ ^{0}<em>{1} \beta \rightarrow ^{0}</em>{1} \gamma + ^{1}_{1} \beta ]</td>
<td>+1</td>
<td>0</td>
<td>NZ too large</td>
<td></td>
</tr>
<tr>
<td>Positron emission (β⁺)</td>
<td>3e</td>
<td>[ ^{0}<em>{-1} \beta \rightarrow ^{0}</em>{-1} \gamma + ^{1}_{1} \beta ]</td>
<td>-1</td>
<td>0</td>
<td>NZ too small</td>
<td></td>
</tr>
<tr>
<td>Electron capture (EC)</td>
<td>x rays</td>
<td>[ ^{0}<em>{-1} \text{e} \rightarrow ^{0}</em>{-1} \text{e} ]</td>
<td>-1</td>
<td>0</td>
<td>NZ too small</td>
<td></td>
</tr>
<tr>
<td>Gamma emission (γ)</td>
<td>3γ</td>
<td>[ ^{0}<em>{0} \gamma \rightarrow ^{0}</em>{0} \gamma ]</td>
<td>0</td>
<td>0</td>
<td>Excited</td>
<td></td>
</tr>
</tbody>
</table>

Spontaneous Fission

- large, heavy radioactive nuclei may spontaneously break into smaller particles
  - “daughter” nuclei
  - smaller nuclei are inherently more stable
- spontaneous fission may also produce neutrons that can cause further fission reactions
- example:
  \[ ^{254}_{98} \text{Cf} \rightarrow ^{118}_{46} \text{Pd} + ^{132}_{52} \text{Te} + 4 ^{0}_{-1} \text{n} \]

example:
Write the balanced equation for β-emission from magnesium-28.

example:
Write the balanced equation for positron emission from \(^{118}\text{Xe}\).

example:
What particle is produced by the decay of \(^{214}\text{Th}\) to \(^{210}\text{Ra}\)?
Decay Series

Nuclear Stability

stability in nuclear terms . . .

- a stable nuclide is one whose radioactive decay $t_{1/2}$ can be measured
- an unstable nuclide is one that decays too fast for $t_{1/2}$ to be measured
- nonradioactive nuclides do not undergo radioactive decay

The Band of Nuclear Stability

- stability of a nuclide is related to the $n:p$ ratio in the nucleus
- as the atomic number increases, for stable nuclei $n:p > 1$
- can sometimes predict the type of radioactive decay by considering the $n:p$ ratio

Summary of Nuclear Reactions

- for nuclides with atomic number $> 83$, $\alpha$-emission is common
- for nuclides with higher $n:p$, $\beta$-emission is more likely decrease $n:p$ as $n \rightarrow p + \beta$
- for nuclides with lower $n:p$, processes like $\beta^+$-emission and $e^-$ capture are more likely increase $n:p$
Kinetic Considerations for Radioactive Decay

- radioactive decay follows 1\textsuperscript{st} order kinetics
- decay rate \( \propto N \)
  \( N \) = number of radioactive nuclei in sample
- \( k \) 1\textsuperscript{st} order rate constant, or decay constant
  units \( t^{-1} \)
- rate law: \( \text{decay rate} = kN \)
- integrated rate law: \( \ln\left(\frac{N}{N_0}\right) = -kt \)
- half-life: \( t_{\frac{1}{2}} = \frac{0.693}{k} \)

Combining Integrated Rate Law and \( t_{\frac{1}{2}} \) Equation:

\[
\ln\left(\frac{N}{N_0}\right) = -kt \quad k = \frac{0.693}{t_{\frac{1}{2}}}
\]

OR

\[
\ln\left(\frac{N}{N_0}\right) = -0.693\left(\frac{t}{t_{\frac{1}{2}}}\right)
\]

example:

Phosphorus-32 is a radioisotope used in leukemia therapy with \( t_{\frac{1}{2}} = 14.28 \) days. What % of radionuclei remain (unreacted) after 35.0 days?
Nuclear Fission

- fission: large nuclei gain stability by breaking into smaller pieces (daughter nuclei)
- frequently a multi-step process or decay series
- frequently neutrons or other particles are produced that can go on to trigger more fission reactions

Critical Mass

- critical mass – the mass of fissionable material required to result in a self-sustained chain reaction

Fusion Reactions

- small nuclei gain stability by fusing together to form larger nuclei
- fusion reactions are common in space, in stars:
  - some examples:
    \[ ^1H + ^1H → ^2H + β^+ \]
    \[ ^1H + ^2H → ^3He \]
    \[ ^3He + ^3He → α + 2 ^1H \]
    \[ ^3He + ^1H → α + β^+ \]

Need a study break? Go to YouTube and search for “They Might Be Giants – Why Does the Sun Shine”. Enjoy!
“Cold” Fusion

- **goal**: active research trying to achieve “cold” fusion
  - harness the energy of fusion reactions
  - use of H isotopes as reactants . . . cheap, plentiful, safe

- **problem**: fusion reactions are *thermonuclear* rxns
  - very large amounts of energy (i.e. very high T; 40 million K) are required to initiate the rxn
  - *but* . . . the energy payback is several orders of magnitude than the energy investment