Chapter 21
Nuclear Chemistry:
the study of nuclear reactions

Learning goals and key skills:
- Write balanced nuclear equations
- Know the difference between fission and fusion
- Predict nuclear stability in terms of neutron-to-proton ratio
- Calculate ages of objects or amounts of materials from data on nuclear abundances using the half-life of a radioactive material
- Convert between nuclear activity units
- Calculate mass and energy changes for nuclear reactions
- Understand the meaning of radiation dosage terms
- Understand the biological effects of different kinds of radiation

The nucleus

The nucleus is comprised of the two nucleons: protons (p⁺) and neutrons (n⁰)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Mass number</th>
<th>Atomic number (optional)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>12</td>
<td>6</td>
</tr>
</tbody>
</table>

Atomic number: equal to the number of protons in the nucleus. All atoms of the same element have the same number of protons.

Mass number: equal to the sum of the number of protons and neutrons for an atom.
Isotopes

Atoms with identical atomic numbers but different mass numbers

\[
\begin{align*}
12 & \quad \text{C} & \quad \text{carbon-12} \\
6 & & \\
1 & \quad \text{H} & \quad \text{Hydrogen or protium} \\
1 & & \\
14 & \quad \text{C} & \quad \text{carbon-14} \\
6 & & \\
2 & \quad \text{H} & \quad \text{deuterium, D} \\
1 & & \\
3 & \quad \text{H} & \quad \text{tritium, T} \\
1 & & \\
\end{align*}
\]

Isotopes

Radionuclides are nuclei that are radioactive – i.e., they will spontaneously emit radiation. Atoms containing these nuclei are called radioisotopes. Some nuclides (radionuclides) of an element are unstable, or radioactive. There are several ways radionuclides can decay into a different nuclide.

\[
\begin{align*}
238 & \quad \text{U} & \quad \text{abundance:} & \quad 99.27\% & \quad \text{half-life} & \quad 4.47 \text{ billion years} \\
92 & & & & & \\
235 & \quad \text{U} & \quad 0.72\% & \quad 700 \text{ million years} \\
92 & & & & & \\
234 & \quad \text{U} & \quad 0.0055\% & \quad 246,000 \text{ years} \\
92 & & & & & \\
\end{align*}
\]
### Table 21.1 Properties of Alpha, Beta, and Gamma Radiation

<table>
<thead>
<tr>
<th>Property</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>$2^+$</td>
<td>$1^-$</td>
<td>$0$</td>
</tr>
<tr>
<td>Mass</td>
<td>$6.64 \times 10^{-24}$ g</td>
<td>$9.11 \times 10^{-28}$ g</td>
<td>$0$</td>
</tr>
<tr>
<td>Relative penetrating power</td>
<td>$1$</td>
<td>$100$</td>
<td>$10,000$</td>
</tr>
<tr>
<td>Nature of radiation</td>
<td>$^2$He nuclei</td>
<td>Electrons</td>
<td>High-energy photons</td>
</tr>
</tbody>
</table>

**α, β, and γ Radiation**

$\beta$-ray $\rightarrow$ High speed electron: charge = $-1$, mass = $9.11 \times 10^{-28}$ g

$\alpha$-ray $\rightarrow$ He core: charge = $+2$, mass = $7295 \times$ mass of electron

$\gamma$-ray $\rightarrow$ Electromagnetic Radiation: no charge, no mass

<table>
<thead>
<tr>
<th>Symbol</th>
<th>$\alpha$-ray</th>
<th>$\beta$-ray</th>
<th>$\gamma$-ray</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^4_2$ He</td>
<td>$^0_1$ e</td>
<td>$^0_0$ γ</td>
</tr>
</tbody>
</table>

0.5 cm of lead

10 cm of lead
Other common nuclear particles

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Neutron</th>
<th>Proton</th>
<th>Positron</th>
</tr>
</thead>
<tbody>
<tr>
<td>charge</td>
<td>0</td>
<td>1+</td>
<td>1+</td>
</tr>
<tr>
<td>mass</td>
<td>$1.675 \times 10^{-24}$ g</td>
<td>$1.673 \times 10^{-24}$ g</td>
<td>$9.11 \times 10^{-28}$ g</td>
</tr>
<tr>
<td></td>
<td>1.00867 amu</td>
<td>1.00728 amu</td>
<td>0.00549 amu</td>
</tr>
</tbody>
</table>

Table 21.2  Particles Found in Nuclear Reactions

<table>
<thead>
<tr>
<th>Particle</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron</td>
<td>$\text{n or n}$</td>
</tr>
<tr>
<td>Proton</td>
<td>$\text{H or p}$</td>
</tr>
<tr>
<td>Electron</td>
<td>$\text{e}$</td>
</tr>
<tr>
<td>Alpha particle</td>
<td>$\text{He or } ^4\alpha$</td>
</tr>
<tr>
<td>Beta particle</td>
<td>$\text{e or } ^{\pm}\beta$</td>
</tr>
<tr>
<td>Positron</td>
<td>$\text{e or } ^{+}\beta$</td>
</tr>
</tbody>
</table>

Types of Radioactive Decay

Table 21.3  Types of Radioactive Decay

<table>
<thead>
<tr>
<th>Type</th>
<th>Nuclear Equation</th>
<th>Change in Atomic Number</th>
<th>Change in Mass Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha emission</td>
<td>$\frac{1}{2}X \rightarrow \frac{1}{2}Y + \frac{4}{4}\text{He}$</td>
<td>-2</td>
<td>-4</td>
</tr>
<tr>
<td>Beta emission</td>
<td>$\frac{1}{2}X \rightarrow z_{\frac{1}{2}}Y + \frac{4}{4}\text{e}$</td>
<td>+1</td>
<td>Unchanged</td>
</tr>
<tr>
<td>Positron emission</td>
<td>$\frac{1}{2}X \rightarrow z_{\frac{1}{2}}Y + \frac{4}{4}\text{e}$</td>
<td>-1</td>
<td>Unchanged</td>
</tr>
<tr>
<td>Electron capture*</td>
<td>$\frac{1}{2}X + \frac{4}{4}\text{e} \rightarrow z_{\frac{1}{2}}Y$</td>
<td>-1</td>
<td>Unchanged</td>
</tr>
</tbody>
</table>

*The electron captured comes from the electron cloud surrounding the nucleus.
Nuclear reactions

Balance using conservation principles, *baryon number conservation*.

**Alpha decay**

Radium-226 emits an alpha particle.

\[
{^{226}_{88}}\text{Ra} \rightarrow {^4_2}\text{He} + {^{222}_{86}}\text{Rn}
\]

**Beta decay**

An unstable neutron in the nucleus will emit a beta particle.

\[
{^1_0}\text{n} \rightarrow {^0_{-1}}\beta + {^1_1}\text{p}
\]

Carbon-14 undergoes beta decay.

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

**Gamma emission**

An excited nuclear state emits gamma radiation.

(Generally not shown when writing nuclear equations.)

Uranium-238 undergoes alpha decay and then gamma emission.

Technetium-99 is metastable and undergoes gamma emission.

(Half-life is 6 hours.)
Nuclear reactions

Positron emission

A neutron-poor nuclei will undergo positron emissions.

\[ \begin{align*}
    _1^1p & \rightarrow _0^0\beta + _1^1n \\

de & \rightarrow e + B
\end{align*} \]

Carbon-11 undergoes positron emission.

\[ \begin{align*}
    _{11}^{11}C & \rightarrow _{0}^{0}e + _{5}^{11}B
\end{align*} \]

Nuclear reactions

Electron capture (K-capture)

A neutron-poor nucleus can decay by positron emission or electron capture.

\[ \begin{align*}
    _1^1p + _0^{-1}e & \rightarrow _1^0n
\end{align*} \]

Iron-55 decays by electron capture.
-Any atom with more than one proton will have repulsions between the protons in the nucleus.

-Strong nuclear force helps keep the nucleus together, key role of ratio of neutrons to protons.

Belt of stability

Only $^1$H and $^3$He have more $p^+$ than $n^0$.

- Up to $Z = 20$ (Ca), $n^0/p^+ \approx 1$.
- Above $Z = 20$, $n^0/p^+ > 1$.
- After $Z = 83$ (Bi), all isotopes are unstable.

For unstable nuclei:
- the heavier, the shorter the half-life.
- the further from the line, the shorter the half-life.

Predicting nuclear decay

too high $N$: $\beta$ emission

too high $N$ and $Z$ ($\geq 84$): $\alpha$ emission

too high $Z$: $\beta^+$ emission

too high $Z$: electron capture

Nuclei with $Z \geq 84$, dominant decay mode = alpha emission

Nuclei above belt of stability, dominant decay mode = beta emission

Nuclei below belt of stability, dominant decay mode = positron emission or electron capture
Radioactive/nuclear disintegration series

- Large radioactive nuclei cannot stabilize by undergoing only one nuclear transformation.

- They undergo a series of decays until they form a stable nuclide (often a nuclide of lead).

Example

The radioactive series beginning with uranium-238 ($Z = 92$) terminates with lead-206 ($Z = 82$). How many alpha decays occur, and how many beta decays occur?
Nuclei with
• 2, 8, 20, 28, 50, 82, 126, or 184 p+
• 2, 8, 20, 28, 50, 82, 126, or 184 n^0
are generally more stable than other nuclei.
• “Magic numbers”
Nuclear transformations

A nucleus can be transformed when it is struck by a neutron or another nucleus. This type of reaction is called a nuclear transmutation.

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

target \quad bombarding \quad ejected \quad product

nucleus \quad particle \quad particle \quad nucleus

Target nucleus \quad Product nucleus

\[ ^{14}\text{N} \quad (\alpha, \text{p})^{17}\text{O} \]

Bombarding particle \quad Ejected particle

Nuclear kinetics: first-order process

\[
\ln \frac{N_t}{N_0} = -kt
\]

\[
\frac{0.693}{k} = t_{1/2}
\]
Half-life is the time required for half of a radionuclide sample to decay.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-Life (yr)</th>
<th>Type of Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{235}\text{U}$</td>
<td>$4.5 \times 10^9$</td>
<td>Alpha</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>$7.0 \times 10^8$</td>
<td>Alpha</td>
</tr>
<tr>
<td>$^{232}\text{Th}$</td>
<td>$1.4 \times 10^{10}$</td>
<td>Alpha</td>
</tr>
<tr>
<td>$^{39}\text{K}$</td>
<td>$1.3 \times 10^9$</td>
<td>Beta</td>
</tr>
<tr>
<td>$^{14}\text{C}$</td>
<td>5700</td>
<td>Beta</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-Life (yr)</th>
<th>Type of Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{241}\text{Pu}$</td>
<td>24,000</td>
<td>Alpha</td>
</tr>
<tr>
<td>$^{137}\text{Cs}$</td>
<td>30.2</td>
<td>Beta</td>
</tr>
<tr>
<td>$^{89}\text{Sr}$</td>
<td>28.8</td>
<td>Beta</td>
</tr>
<tr>
<td>$^{122}\text{I}$</td>
<td>0.022</td>
<td>Beta</td>
</tr>
</tbody>
</table>

**Rates of decays**

**activity**: rate at which a sample decays, disintegrations per unit time, typically measured in dps (disintegrations per second)

**becquerel (Bq)**: SI unit for activity.  
1 Bq = 1 dps

**curie (Ci)**: rate of decay of 1 g of radium.  
1 Ci = $3.7 \times 10^{10}$ dps
Kinetics of Radioactive Decay: Radiometric Dating

A wooden object from an archeological site is subjected to radiocarbon dating. The activity of the sample that is due to $^{14}\text{C}$ is measured to be 11.6 disintegrations per second. The activity of a carbon sample of equal mass from fresh wood is 15.2 disintegrations per second. The half-life of $^{14}\text{C}$ is 5715 yr. What is the age of the archeological sample?

Example

A 1.0 mg sample of uranium-238 decays at a rate of 12 alpha emissions per second = 12 dps. Find the half-life of uranium-238.
**Measuring Radioactivity**

Film badges (spots on the developed film) and phosphors (measure the amount of light emitted by a phosphor in a scintillation counter) are used to measure the amount of activity present in a radioactive sample.

- The ionizing radiation creates ions, which conduct a current that is detected by the instrument.

**Radiotracers**

Radiotracers: radioisotopes used to study a chemical reaction. An element can be followed through a reaction to determine its path and better understand the mechanism of a chemical reaction.

- Radioisotopes are administered to a patient (usually intravenously) and followed. Certain elements collect more in certain tissues, so an organ or tissue type can be studied based on where the radioactivity collects.

**TABLE 21.6 Some Radionuclides Used as Radiotracers**

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Half-Life</th>
<th>Area of the Body Studied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iodine-131</td>
<td>8.04 days</td>
<td>Thyroid</td>
</tr>
<tr>
<td>Iron-59</td>
<td>44.5 days</td>
<td>Red blood cells</td>
</tr>
<tr>
<td>Phosphorus-32</td>
<td>14.3 days</td>
<td>Eyes, liver, tumors</td>
</tr>
<tr>
<td>Technetium-99a</td>
<td>6.0 hours</td>
<td>Heart, bones, liver, and lungs</td>
</tr>
<tr>
<td>Thallium-201</td>
<td>73 hours</td>
<td>Heart, arteries</td>
</tr>
<tr>
<td>Sodium-24</td>
<td>14.8 hours</td>
<td>Circulatory system</td>
</tr>
</tbody>
</table>

*aThe isotope of technetium is actually a special isotope of Tc-99 called Tc-99m, where the m indicates a so-called metastable isotope.
Nuclear binding energy

The mass difference between a nucleus and its constituent nucleons is called the mass defect. We can use Einstein’s equation to find the nuclear binding energy: the energy required to separate a nucleus into its individual nucleons.

\[ E = mc^2 \]

1 eV = 1.602 \times 10^{-19} \text{ J}

c = 2.99792458 \times 10^8 \text{ m s}^{-1}

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3\text{He}$</td>
<td>4.00380</td>
<td>4.03188</td>
<td>0.02808</td>
<td>4.53 \times 10^{-12}</td>
<td>1.51 \times 10^{-12}</td>
</tr>
<tr>
<td>$^{56}\text{Fe}$</td>
<td>56.92068</td>
<td>56.44914</td>
<td>0.47136</td>
<td>7.90 \times 10^{-11}</td>
<td>1.41 \times 10^{-12}</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>238.00031</td>
<td>238.93451</td>
<td>0.93420</td>
<td>2.89 \times 10^{-10}</td>
<td>1.21 \times 10^{-12}</td>
</tr>
</tbody>
</table>

Example

Calculate the nuclear binding energy for deuterium.

$^1\text{H}$ + $^1\text{n}$ → $^2\text{H}$

1.007825 amu  1.008665 amu  2.01410 amu

The mass defect is 0.00239 amu.

Avogadro Constant = 6.0221421 \times 10^{23} \text{ mol}^{-1}
mass of electron = 5.4857 \times 10^{-4} \text{ amu}
mass of neutron = 1.008665 \text{ amu}
mass of proton = 1.007276 \text{ amu}
Example

Calculate the nuclear binding energy per mole for deuterium.

\[
\begin{array}{c}
\text{1.007825 amu} \\
\text{1.008665 amu} \\
\text{2.01410 amu}
\end{array}
\]

The mass defect is 0.00239 amu.

Example

Calculate the nuclear binding energy per nucleon for deuterium.

\[
\begin{array}{c}
\text{1.007825 amu} \\
\text{1.008665 amu} \\
\text{2.01410 amu}
\end{array}
\]

The mass defect is 0.00239 amu.
Nuclear binding energies

- Heavy nuclei gain stability and give off energy when they split into two smaller nuclei. This is **fission**.
- Lighter nuclei emit great amounts of energy by being combined in **fusion**.

![Diagram showing binding energy per nucleon and mass number](image)

**Nuclear Fission**

Fermi’s proposed transuranium synthesis

\[
\begin{align*}
^{238}_{92}\text{U} + ^{1}_{0}\text{n} & \rightarrow ^{239}_{92}\text{U} \rightarrow ^{239}_{93}\text{X} + ^{0}_{-1}\beta \\
^1\text{n} + ^{235}_{92}\text{U} & \leftrightarrow ^{137}_{52}\text{Te} + ^{97}_{40}\text{Zr} + 2^1_0\text{n} \\
& \leftrightarrow ^{142}_{56}\text{Ba} + ^{91}_{36}\text{Kr} + 3^1_0\text{n}
\end{align*}
\]

Meitner, Strassman, Hahn discovered U-235 didn’t make a new element, but …
• Bombardment of the radioactive nuclide with a neutron starts the process.
• More neutrons are produced from the transmutation.
• A critical mass of radioactive nuclides is needed for a self-sustaining chain reaction.

• The minimum mass that must be present for a chain reaction to be sustained is called the critical mass.
• If more than critical mass is present (supercritical mass), an explosion will occur. Weapons were created by causing smaller amounts to be forced together to create this mass.
Nuclear reactors

In nuclear reactors, the heat generated by the reaction is used to produce steam that turns a turbine connected to a generator.

The reaction is kept in check by the use of control rods made of boron carbide, Ag, In, Cd, or Hf.

These block the paths of some neutrons, keeping the reactor core from overheating.
Nuclear waste

- Reactors must be stopped periodically to replace or reprocess the nuclear fuel.
- They are stored in pools at the reactor site.
- The original intent was that this waste would then be transported to reprocessing or storage sites, but politics....

Nuclear fusion

- Potentially superior method of generating power
- Need ~40,000,000 K for any fusion reaction.

A tokamak fusion test reactor has only been able to get 100,000,000 K – but not stable and has not yet produced more power than it takes to use.
Origin of the elements

produces

yellow stars  
$^1$H fusion  
He

red giants  
$^4$He fusion  
C, O, Ne, Mg

red supergiants  
$^4$He + $^{12}$C  
Na, Si, S, Ar, Ca

$^{12}$C + $^{12}$C  
Fe, Ni

$^{12}$C + $^{16}$O

supernovae, neutron stars  
$^{56}$Fe + $^1$n  
Z > 28

Radiation in the Environment

- **Ionizing radiation** is more harmful to living systems than **nonionizing radiation**, such as radiofrequency electromagnetic radiation.
- Since most living tissue is ~70% water, ionizing radiation is that which causes water to ionize.
  \[
  \text{H}_2\text{O}^+ + \text{H}_2\text{O} \rightarrow \text{H}_3\text{O}^+ + \text{OH}
  \]
- This creates unstable, very reactive OH radicals, which result in much cell damage.
- The damage to cells depends on the type of radioactivity, the length of exposure, and whether the source is inside or outside the body.
- Outside the body, gamma rays are most dangerous.
- Inside the body, alpha radiation can cause most harm.
Constant exposure to radiation.

### Radiation doses

**gray (Gy):** SI unit of absorbed dose  
1 Gy = absorption of 1 J/kg tissue

**rad:** radiation absorbed dose  
1 rad = absorption of 0.01 J/kg tissue  
1 Gy = 100 rads

**RBE:** relative biological effectiveness  
RBE (β and γ) = 1  
RBE (α) = 10

**rem** = (# rads) (RBE)  
*roentgen* equivalent for *man*

**sievert (Sv)** SI unit for dosage  
1 Sv = 100 rem, 1 mSv = 0.1 rem

### Table 21.8 Average Abundances and Activities of Natural Radionuclides

<table>
<thead>
<tr>
<th></th>
<th>Potassium-40</th>
<th>Rubidium-87</th>
<th>Thorium-232</th>
<th>Uranium-238</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land elemental abundance (ppm)</td>
<td>28,000</td>
<td>112</td>
<td>10.7</td>
<td>2.8</td>
</tr>
<tr>
<td>Land activity (Bq/kg)</td>
<td>870</td>
<td>102</td>
<td>43</td>
<td>35</td>
</tr>
<tr>
<td>Ocean elemental concentration (mg/L)</td>
<td>1.89</td>
<td>0.12</td>
<td>1 × 10^-7</td>
<td>0.0012</td>
</tr>
<tr>
<td>Ocean activity (Bq/L)</td>
<td>12</td>
<td>0.11</td>
<td>4 × 10^-7</td>
<td>0.040</td>
</tr>
<tr>
<td>Ocean sediments elemental abundance (ppm)</td>
<td>17,000</td>
<td>—</td>
<td>5.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Ocean sediments activity (Bq/kg)</td>
<td>500</td>
<td>—</td>
<td>20</td>
<td>12</td>
</tr>
<tr>
<td>Human body activity (Bq)</td>
<td>4000</td>
<td>600</td>
<td>0.08</td>
<td>0.4</td>
</tr>
</tbody>
</table>


2 Includes lead-210 and polonium-210, daughter nuclei of uranium-238.
Short-Term Exposure

22

• Average individual background radiation dose: 0.34 μSv/h or 3.0 mSv/year for Americans
• Dental radiography: 0.005 mSv
• Average dose to people living within 16 km of Three Mile Island accident: 0.08 mSv during the accident
• Mammogram: 3 mSv
• Brain CT scan: 0.8–5 mSv
• Chest CT scan: 6–18 mSv
• Gastrointestinal series X-ray investigation: 14 mSv
• Current average limit for nuclear workers: 20 mSv per year
• Dose from smoking 30 cigarettes a day: 13-60 mSv/year (0.04 picocuries of polonium 210)
• Criterion for relocation after Chernobyl: 350 mSv/lifetime
• Typical dose near Chernobyl reactor 4 and its fragments, shortly after explosion: ≈ 10–300 mSv/hour
• March 16, 2011, a radiation level of 300 mSv/h was recorded between the exteriors of the secondary containment buildings of Unit 2 reactor and Unit 3 reactor of Fukushima Daiichi Nuclear Power Station.
• In Fukushima Prefecture, the level in the town of Namie (20 km), which peaked at 170 μSv/h at 2 p.m. on March 17, 2011 fell to 25.2 μSv/h as of April 10. The accumulated radiation for the March 23 to April 9 period was 13.95 mSv. Radiation levels have also fallen to 1.8 μSv/h (24.24 μSv/h at peak time) in Fukushima city.

• 600 rem is fatal to most humans.
Average exposure per year is about 360 mrem.

- Radon-222 is a decay product of uranium-238, which is found in rock formations and soil.
- Most of the decay products of uranium remain in the soil, but radon is a gas.
- When inhaled, it can cause significant harm, since the decay produces alpha particles, which have a high RBE.
- It is estimated to contribute to 10% of all lung cancer deaths in the United States.
BNCT
Boron Neutron Capture Therapy

- $^{10}\text{B}$ can capture slow neutrons
- Tumor cells preferentially take up boron compounds
- $^{10}\text{B} + ^1\text{n} \rightarrow ^{11}\text{B}^* \rightarrow ^7\text{Li} + 4\alpha$

Food irradiation

- Food can be irradiated with $\gamma$ rays from $^{60}\text{Co}$ or $^{137}\text{Cs}$.
- Irradiated milk has a shelf life of 3 months without refrigeration.
- USDA has approved irradiation of meats and eggs.