NUCLEAR STABILITY

Rules:
1) Up to atomic number 20, n=p is stable.
2) Above atomic number 20, n>p is stable.
3) Above atomic number 83 (Bi), all nuclei are unstable (radioactive).
4) Nuclei with 2, 8, 20, 28, 50, or 82 protons, or 2, 8, 20, 28, 50, 82, or 126 neutrons are particularly stable. These are the nuclear equivalent of closed shell configurations (and are called magic numbers).
5) Even numbers of protons and neutrons are more stable.

# of Stable Nuclei
With This
Configuration: # Protons # Neutrons
157 Even Even
52 Even Odd
50 Odd Even
5 Odd Odd

An isotope that is off the belt of stability can undergo one of four nuclear reactions to get to it:
1. α decay
2. β decay
3. positron emission
4. electron capture
Getting Back to the Belt of Stability!

NUCLEAR STABILITY: High neutron/proton ratio

An isotope with a high n/p ratio is proton deficient.

To convert neutrons to protons, it can undergo $\beta$-decay:

$^{1}_0 n \rightarrow$

$^{97}_{40} Zr \rightarrow$
NUCLEAR STABILITY: Low neutron/proton ratio

An isotope with a low n/p ratio is neutron deficient.

To convert protons to neutrons, there are two possibilities:

i) Positron emission:
\[ ^1_1p \rightarrow ^1_0n + ^0_1e \]

\[ ^{20}_{11}\text{Na} \rightarrow \]

ii) Electron capture:
\[ ^1_1p + ^0_{-1}e \rightarrow ^1_0n \]

Nuclei with Atomic Numbers greater than or equal to 84

Undergo \( \alpha \)-decay in order to reduce both the numbers of neutrons and protons:

Example:
\[ ^{235}_{92}\text{U} \rightarrow ^{231}_{90}\text{Th} + ^4_2\text{He} \]
Nuclear Decay Summary

<table>
<thead>
<tr>
<th>Decay Type</th>
<th>Reactants</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )-decay</td>
<td>element(_1) \rightarrow 4^2He + element(_2)</td>
<td>AN &gt; 83</td>
</tr>
<tr>
<td>( \beta )-decay</td>
<td>( ^0_1n \rightarrow ^1_0p + ^0_1e )</td>
<td>n/p high</td>
</tr>
<tr>
<td>Positron</td>
<td>( ^1_1p \rightarrow ^0_1n + ^0_1e )</td>
<td>n/p low light nuclei</td>
</tr>
<tr>
<td>Electron Capture</td>
<td>( ^1_1p + ^0_1e \rightarrow ^0_1n )</td>
<td>n/p low heavy nuclei</td>
</tr>
</tbody>
</table>

Cascade of \( \alpha \) and \( \beta \) decay reactions

Moves diagonally down belt of stability

Eventually gets to stable isotope \( ^{206}_{\text{Pb}} \)
Detection of Radioactivity

Geiger Counter

![Geiger Counter diagram]

Effects of Radiation

**TABLE 21.7 Effects of Short-Term Exposures to Radiation**

<table>
<thead>
<tr>
<th>Dose (rem)</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–25</td>
<td>No detectable clinical effects</td>
</tr>
<tr>
<td>25–50</td>
<td>Slight, temporary decrease in white blood cell counts</td>
</tr>
<tr>
<td>100–200</td>
<td>Nausea; marked decrease in white blood cells</td>
</tr>
<tr>
<td>500</td>
<td>Death of half the exposed population within 30 days after exposure</td>
</tr>
</tbody>
</table>
Sources of Exposure to Radiation

NUCLEAR DECAY KINETICS

What is the order of the process for nuclear decay?

\[ N \to P \]

Decay Rate = The Activity of the sample

Rate =

\[ k \] is the decay constant,
\[ N \] is the number of decaying nuclei.

*Activity is expressed in Bq*

Example Problem: A sample of \(^{90}\text{Sr}\) has an Activity of \(5.1 \times 10^{12} \text{ Bq}\) and a decay constant of \(7.64 \times 10^{-10} \text{ s}^{-1}\). How many atoms are in the sample?
First Order Decay Kinetics

What is decay dependent upon?
- T?
- P?
- Collisions?
- Activation Energy?

Integrated rate law:

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

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

where \( N_0 \) is the number of radioactive nuclei at \( t=0 \).

Nuclear Half-Life

Define Half-Life:

At the time required for 1 half-life,

\[ \frac{N_t}{N_0} = \frac{1}{2} \]

\[ \ln \left( \frac{1}{2} \right) = -k \frac{t_1}{2} \]

\[ t_1 = \frac{1}{2} \]

Isotope  \( t_1 \)  Mode of Decay

\( ^{238}_{92}\text{U} \)  \( 4.5 \times 10^9 \text{ yr} \)  \( \alpha \)

\( ^{235}_{92}\text{U} \)  \( 7.1 \times 10^8 \text{ yr} \)  \( \alpha \)

\( ^{239}_{94}\text{Pu} \)  \( 2.4 \times 10^4 \text{ yr} \)  \( \alpha \)

\( ^{14}_{6}\text{C} \)  \( 5.7 \times 10^3 \text{ yr} \)  \( \beta \)
Example Problem:
Strontium-90, which is a fission product of uranium, has a half-life of 28 years. This isotope is a significant environmental concern.

What fraction of $^{90}$Sr produced today will remain after 100 years?

Carbon Dating
Libby developed a method in 1946 of determining age using $^{14}$C. $^{14}$C is produced by cosmic radiation; capture of neutrons by nitrogen in the upper atmosphere.

$^{14}_7$N + $^1_0$n $\rightarrow$ $^{14}_6$C + $^1_1$H  7.5 kg/year

It decays
$^{14}_6$C $\rightarrow$ $^{14}_7$N + $^0$e $^-_1$e  $t_{1/2}$ = $5.73 \times 10^3$ years

Living organisms contain C, and $^{14}$C emits beta particles at a rate of 14 dpm (dpm = disintegrations/min). When the specimen dies, the $^{14}$C is not replaced (intake of fuel stops), and the number of disintegrations slowly diminishes.

Example: The dead sea scrolls (papyrus) emit 11 dpm/g. What is the age of this document?
Dating the Earth

- $^{238}\text{U}$ decays into $^{206}\text{Pb}$
- Use the amount of $^{238}\text{U} \ (g\ Ut)$ and the amount of $^{206}\text{Pb}$ present at time $t$ to date rocks:

- Calculate the mass of $\text{U}$ that decomposed and turned into $\text{Pb}$

- Calculate the total weight of $\text{U}$ before any of it decomposed ($g\ Ut_o$)

- To calculate $t$, substitute ratio into integrated rate law:
  \[
  \frac{g\ Ut}{g\ Ut_o} = \frac{N_t}{N_o}
  \]

Masses of nuclei are always less than the sum of the masses of the nucleons

$^4_2\text{He} \rightarrow 2^1_1\text{p} + 2^1_0\text{n}$

Mass defect = products - reactants

$^1_1\text{p} \quad \text{mass is } 1.00728 \text{ amu}$

$^1_0\text{n} \quad \text{mass is } 1.00867 \text{ amu}$

$^4_2\text{He} \quad \text{mass is } 4.00150 \text{ amu}$

\[
\text{Mass defect} = (2)(1.00728 \text{ amu}) + (2)(1.00867 \text{ amu}) - 4.00150 \text{ amu}
\]

$\Delta m = +0.03040 \text{ amu} \quad \text{(gain of mass)}$
Nuclear BINDING ENERGY

Binding energy is:

\[ E = mc^2 \]

Probably better to write:
\[ \Delta E = (\Delta m)c^2 \]

Convert mass defect to kg:

Calculate Binding Energy:
\[ \Delta E = (5.047 \times 10^{-29} \text{ kg})(3 \times 10^8 \text{ m/sec})^2 \]
\[ \Delta E = 4.543 \times 10^{-12} \text{ J} / ^4\text{He nucleus} \]
\[ \Delta E = 2.736 \times 10^{12} \text{ J} / \text{mole} \]

Compare to \( \Delta E \) for a chemical reaction:

\[
\text{Al}(s) + \text{Fe}_2\text{O}_3(s) \rightarrow \text{Al}_2\text{O}_3(s) + \text{Fe}(s)
\]

Compare Binding Energies

Binding energy per nucleon:

Binding Energy per nucleon for \(^4\text{He}\) = \(\frac{(4.54 \times 10^{-12})}{4} = 1.14 \times 10^{-12} \text{ J.}\)

Compare:
\(^4\text{He}: \ 1.14 \times 10^{-12} \text{ J}\)
\(^{56}\text{Fe}: \ 1.41 \times 10^{-12} \text{ J}\)  \(\text{largest BE = most stable nucleus}\)
\(^{238}\text{U}: \ 1.22 \times 10^{-12} \text{ J}\)

Nuclear mass > 50-60 amu: nuclear fission is exothermic

Combined nuclear mass < 50-60: nuclear fusion is exothermic.
Nuclear Binding Energy

- Amount of heat given off when pushing particles together to form a nucleus
- OR
- Amount of Energy required to break apart a nucleus

Larger B.E. = More Stable Nucleus

Increasing Nuclear Stability

- Heavy or light Elements can gain stability by conversion to an element of intermediate mass.
- Light elements can undergo FUSION
- Heavy Elements can undergo FISSION
NUCLEAR FISSION

$^{235}\text{U}$ undergoes fission *hundreds* of different ways:

$$\begin{align*}
\text{n} + ^{235}\text{U} &\rightarrow ^{137}\text{Te} + ^{97}\text{Zr} + 2 \text{n} \\
&\rightarrow ^{142}\text{Ba} + ^{91}\text{Kr} + 3 \text{n}
\end{align*}$$

An average of 2.4 neutrons are produced per $^{235}\text{U}$.

*Only specific nuclei undergo fission; $^{235}\text{U}, ^{239}\text{Pu}, ^{233}\text{U}$*

Extent of Reaction Depends on the Mass Present

_Small_ Amount of mass:

_MEDIUM_ Amount of mass:

_LARGE_ Amount of mass:
Nuclear reactor fuel: This amount of $^{235}\text{U}$ is too small to go supercritical.

Heat is given off by the nuclear reaction:

Where are nuclear reactors usually located?

NUCLEAR REACTORS

Cadmium or boron are used in control rods because?

Moderators:
Nuclear Waste Disposal

Spent fuel contains fission products; decreases efficiency of fission reaction

⇒ Replace fuel rods and reprocess

Problems with disposal of spent fuel:

1) 

2) 

3) 

Nuclear or Atomic Bombs

Main fuel is U-235. Hard to purify:

✓ Uranium ore is concentrated and treated with Fluorine to form UF₆. This is low boiling and can be evaporated at 56°C.

✓ 99.3% is non-fissionable U-238. Chemical reactions don’t help separate isotopes.

✓ Gaseous diffusion separates the heavier particles (UF₆ with U-235 moves 0.4% faster than U-238)

✓ Repeated diffusion over long barriers or centrifugation concentrates U-235

Plutonium bombs
First produced at Hanford, Washington.
Plutonium can be used for bombs or as a fuel source. However, small amounts of PuO₂ dust in air causes lung cancer. Very toxic.
The sun contains 73% H, and 26% He.

\[
\begin{align*}
^1_1H + ^1_1H & \rightarrow ^2_1H + ^0_1e \\
^1_1H + ^2_1H & \rightarrow ^3_2He \\
^3_2He + ^3_2He & \rightarrow ^4_2He + ^2_1H \\
^3_2He + ^1_1H & \rightarrow ^4_2He + ^0_1e
\end{align*}
\]

Initiation of these reactions requires temperatures of \(4 \times 10^7\) K - not currently obtainable on Earth on a stable basis.
**Thermonuclear Bomb, or Hydrogen Bomb**

\[
^6_3\text{Li} + ^1_0\text{n} \rightarrow ^3_1\text{H} + ^4_2\text{He}
\]

\[\Delta E = -1.7 \text{ kJ/mol tritium}\]

The nucleons combine in a high energy plasma (~10^6 K).

To achieve the required high temperature, an atomic bomb must be used to initiate the process.

A 20-megaton bomb has 300 lbs Li-D as well as a fission/atomic bomb.

⇒ Not yet practical for power generation

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**Applications of Nuclear Chemistry**

**Diagnostic Chemical Tools**

NMR (Nuclear Magnetic Resonance)

**Medical Applications**

MRI (Magnetic Resonance Imaging)

Diagnosis and Imaging

PET scans

**Treatment**

Cancer
**Nuclear Spin**

*Example:* $^1\text{H}$ has 2 spin states

- Spin = $+1/2$ (clockwise)
- Spin = $-1/2$ (counterclockwise)

**Magnetic Resonance**

In an external magnetic field of strength $H_0$, a spinning nucleus will *precess* with angular frequency $\omega$.

When incoming radiofrequency $\nu$ is the same as $\omega$, the radiation can be absorbed by the nucleus:

- **nucleus has resonance with incoming frequency: absorption occurs.**

\[ \nu = 60\text{MHz} \]
\[ H_0 = 14,100 \text{ gauss} \]
\[ \omega = 60\text{MHz} \]
\[ \Delta E = h \nu \]
Nuclear Magnetic Resonance (NMR)

1. Liquid or solid sample placed in external magnetic field
2. Apply RF pulse (60MHz, 300MHz)
3. Computers convert emitted pulses to signals shown in spectra.

Absorbed frequency will be shifted due to interaction with electrons in the surrounding molecule.

Resonance frequency depends on the chemical environment of the nucleus of interest.

Proton NMR Spectra

Location of peak in the spectrum is related to location of proton in molecule.

benzene

para-xylene

Height of peak is related to the number of equivalent protons (same chemical environment).
MRI (Magnetic Resonance Imaging)

In MRI a person is the “sample” that is inserted into the magnetic field. Due to the complexity of the “sample”, it is important for the technique to be highly sensitive.

• Exposure to radiation is avoided. Radiowaves are used.

• Distinguishes pathologic tissue (such as tumors) from normal tissue

• Magnetic Field strength is large: typically 30,000 Gauss. Problem for people with pacemakers, metal implants.

• Expensive technique: cost of magnet and maintenance is high

Diagnosis and Imaging; label with radioisotopes

Radiotracing

\[ ^{201}\text{TI} \]  γ - emitter
concentrates in the heart
Used to tell condition of heart and arteries

\[ ^{131}\text{I} \] absorbed by thyroid:
used to measure activity in thyroid

PET (positron emission tomography)
A compound like glucose is labeled with a positron-emitting isotope \( ^{11}\text{C}, ^{18}\text{F}, ^{15}\text{O}, ^{13}\text{N} \)

⇒ Detect positrons, create 3-D images, contrast with normal images.
Cancer Treatment

Cancerous cells are more susceptible to radiation than healthy ones.

$^{60}\text{Co}$ \hspace{1cm} $\gamma$-emitter
used to directly irradiate tumors

$^{192}\text{Ir}$ \hspace{1cm} implanted in tumors
Encapsulated in Pt to contain $\alpha$ and $\beta$ rays
$\gamma$ radiation kills tumor cells