Georgia White
CHEM 1901

# TOPIC 1: Nuclear and radiation chemistry

**Nuclide** - an atom with a particular mass number and atomic number
**Isotopes** - nuclides with the same atomic number (Z) but different mass numbers (A)

## Notation

| | |
|---|---|
| $^{A}_{Z}Element\ symbol$<br>where A = mass number<br>Z = atomic number | $^{12}_{6}C$ |
| Element name - mass number | Carbon-12 |

Subatomic particles → α, β, γ
Effects on reaction rate

- ✓ Shape of reactor
- ✓ Mass of sample
- × Heat
- × Catalyst

**Atomic mass** - the average of the atomic masses and the abundances of each of the naturally occurring isotopes

$$atomic\ mass = (\%\ nat.abundance\ isotope\ 1\ \times mass\ 1) + \cdots + (\%\ nat.abundance\ isotope\ n\ \times mass\ n)$$

## Nuclear equations

$$^{Total\ A}_{Total\ Z}Reactants = ^{Total\ A}_{Total\ Z}Products$$

**Particles involved**

| proton | neutron | electron | positron | gamma ray |
|---|---|---|---|---|
| $^{1}_{1}p$ | $^{1}_{0}n$ | $^{0}_{-1}e$ | $^{0}_{1}e$ | $\gamma$ |

## Stability of nuclides

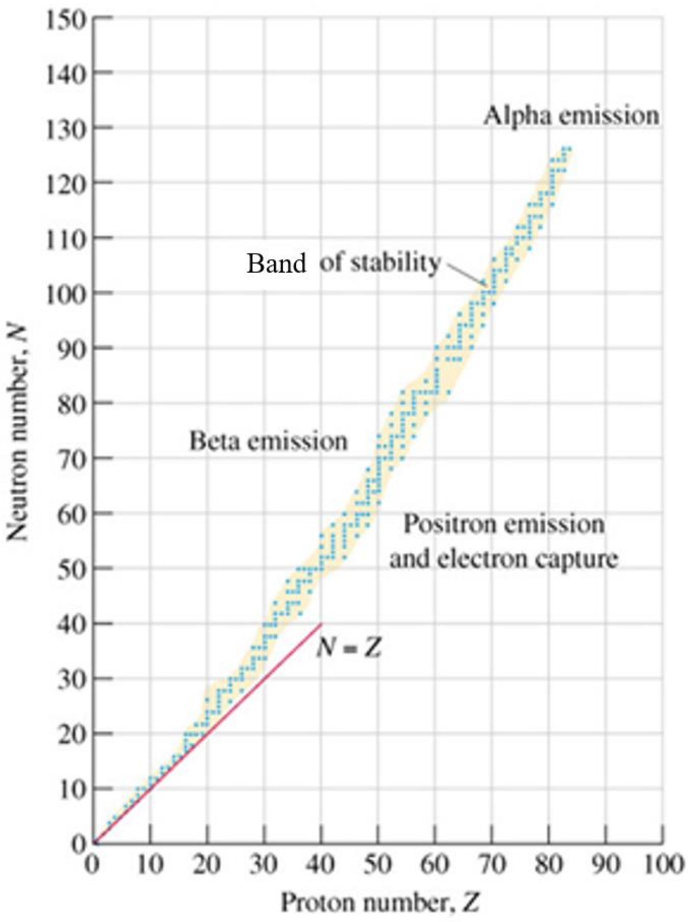
All stable nuclei fall within a **band of stability**

- Lighter nuclei lie on or close to the N=Z line (N:Z=1)
- As Z ↑, N:Z for stability ↑

| | |
|---|---|
| Z = 1-20 | N:Z = 1.1 |
| Z = 20-80 | N:Z = 1.3 |
| Z = 80+ | N:Z = 1.5 |

- **Strong nuclear** (/nuclear binding) **force** – the attractive force that holds the nucleus together
    - Can act over small distances to hold n+p together – at this distance is 1000x greater than p-p repulsion
    - As Z ↑ the effect of p-p repulsion ↑ → ↑ N needed to generate enough nuclear force to stabilise the nucleus

    ⇒ Gradual slope of band of stability
- Radioactive nuclei undergo spontaneous decay → stable nucleus
- Even number of n/p are more stable



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## Modes of decay

An unstable nuclide decays in a mode that shifts its N:Z toward the band of stability

**Size of nucleus** – too large, Z>82 – aim: ↓ n+p

Alpha decay

- Releases helium nucleus ${}^{4}_{2}He$
- A ↓ 4
- Z ↑ 2
- Most effective way to lose mass quickly – ↓ mass with the aim of stability
- Preferred method of decay for heavy nuclei – heavier than Pb i.e. Z>82

**Neutron-rich** – n:p too large – aim: n → p

Beta decay

- ${}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e + \bar{v}_e$
- Electron expelled from nucleus
    - B particles emitted from different radionuclides have different energies – range from 0 to the characteristic fixed upper limit for each radionuclide
    - Seemed to be a violation of energy conservation – β decay is accompanied by emission of an anti-neutrino ($\bar{v}_e$)
        - Electrically neutral
        - Almost massless
- A constant
- Z ↑ 1
- Nuclei above the band of stability – ↓ n:p → closer to band of stability

Neutron emission

- ${}^{1}_{0}n$ emitted e.g. ${}^{7}_{2}He \rightarrow {}^{6}_{2}He + {}^{0}_{1}n$
- A ↓ 1
- Z constant

**Proton-rich** – n:p too low – aim: p → n

<u>Positron decay</u>

- $^{1}_{1}p \rightarrow \ ^{1}_{0}n + \ ^{0}_{1}e + \nu_e$
- Positron expelled from nucleus
- Accompanied by a neutrino ($\nu_e$)
- A constant
- Z ↓ 1
- Positron eventually collides with an electron $^{0}_{1}e + \ ^{0}_{-1}e \rightarrow 2\gamma$
- Nuclei below the band of stability – ↑ n:p → closer to band of stability

<u>Electron capture</u>

- $^{1}_{1}p + \ ^{0}_{-1}e \rightarrow \ ^{1}_{0}n$
- Inner-orbital electron captures by nucleus
- Accompanied by $\nu_e$
- Leaves gaps in inner electron shells → higher orbital electrons drop down → x-rays emitted
- A constant
- Z ↓ 1
- Rare in natural nuclei, common in synthetic

**High energy nucleus**

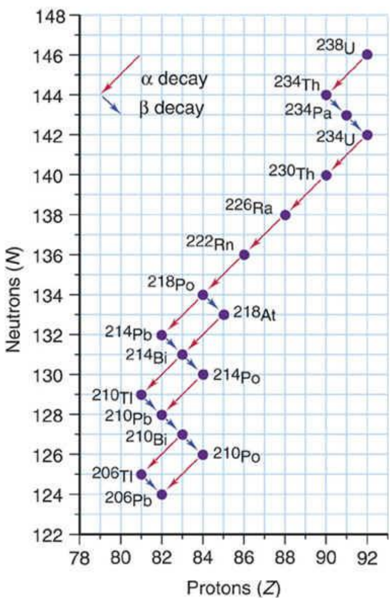
<u>Gamma emission</u> (γ)

- High energy photons emitted from nucleus
- Nucleus loses energy
- Accompanies most other types of decay

**Radioactive decay sequences**

➢ Often a nuclide will require >1 decay to reach stability

- α decay shown as p ↓ 2 and n ↓ 2
- β decay shown as p ↑ 1 and n ↓ 1
- Isotopes (same Z, different N) lie along vertical lines



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## Half-life

**Half-life** – the time required for…

- Half the initial number of nuclei to decay
- The activity of the radiation to halve
- Activity depends on number of nuclei present
- Radioactive decay can be described by an **exponential function**

$$t_{½} = \ln 2/k$$
$$A = kN$$
$$\ln(N_0/N_t) = kt$$

where $N_0$ = number of nuclei initially
$N_t$ = number of nuclei after time t
A = activity ($s^{-1}$ or Bq)
$k$ *or* $\lambda$ = decay constant
$t_{1/2}$ = half life

- $N_0$ and $N_t$ van be substituted for $A_0$ and $A_t$
- $t_{1/2}$ and $\lambda$ are characteristic of each isotope
- short $t_{1/2}$ → very active → high $\lambda$
- $N_0 > N_t$ due to decay

**Specific activity** – activity per gram of radioactive nuclide – Bq/g
**Molar activity** – activity per mole of radioactive nuclide – Bq/mol
*1 Becquerel* = 1 disintegration per second

## Carbon-14 dating

$$^{14}C\ \text{age} = 8033\ \ln(A_0/A_t)\ \text{years}$$

where $A_0$ = activity in a living organism
$A_t$ = activity in an organism now

- Answer: $^{14}C$ age = _ years before 1950

- Estimate age of organic remains e.g. wood, bone
- Objects up to 60,000yo can be dated but more accurate for objects <7,000yo
- Critical assumption – availability of $^{14}C$ from atmosphere has remained largely unchanged over time

In the atmosphere, cosmic rays generate $^{14}_{6}C$

$$^{14}_{7}N + ^{0}_{1}n \rightarrow ^{15}_{7}N \rightarrow ^{14}_{6}C + ^{1}_{1}p$$

→ $^{14}C$ diffuses into lower atmosphere
→ Some of $CO_2$ taken in by plants is $^{14}CO_2$
→ Some things humans eat contain $^{14}CO_2$
→ Every living thing maintains a constant $^{14}C$:$^{12}C$ during lifetime b/c constantly ingesting
→ After death $^{14}C$ decays by β decay
→ $^{14}C$:$^{12}C$ in a dead organism can indicate time since its death

**Uses of radiation**

- Determined by chemical and physical properties

**Factors affecting damage caused by radiation**

- Level of damage caused → effective radiation dose

1. Type of radiation

| Type | Nature/energy | Energy | Penetrating ability Stopped by… | Ionising ability | Relative biological effectiveness (Q) |
|---|---|---|---|---|---|
| α | Stream of particles | High | Low<br>Paper, skin | High | 20<br>Very high |
| β | Stream of particles | Low | Moderate<br>Thin sheet Al | Moderate | 1-1.7<br>Low |
| γ | EM wave | Lower | High<br>Thick sheet Pb | Low | 1<br>Lower |

Relative biological effectiveness = danger caused to living tissue

- α is 20x more effective at destroying living tissue

2. Length of exposure
   - Short term (acute)
     - Radiation poisoning
     - High doses for short periods of time → acute cell damage, death
   - Long term (chronic)
     - Radiation-induced cancer
     - Interrupt DNA → cancer
3. Source of exposure
   - Internal – ingestion/inhalation
     - α/β remain in body and can't escape → dangerous
     - γ escapes body
   - External
     - α/β can't penetrate
     - γ can penetrate → more dangerous

**Biological dangers of ionising radiation**

$H_2O$ + ionising radiation → $H_2O^+ + e^-$ (the body is 50-70% water)

⇒ $H_2O^+ + H_2O \rightarrow H_3O^+ + OH^*$ and $e^- + H_2O \rightarrow OH^- + H^*$

<u>Free radicals</u> (e.g. $OH^*$, $H^*$)

- Very reactive
- DNA → genetic damage, cancer
- Cell membranes → cells break apart
- Proteins → enzymes lose function

## Production of radionuclides

**Fusion** – the joining together of light nuclei to form heavier nuclei
**Fission** – the splitting of heavy nuclei into lighter nuclei

⇒ Both processes produce significant amounts of energy

**Binding energy** – holds nucleons together

- To separate nucleons we must supply this energy

**Nucleogenesis** – the formation of new nuclei from existing nucleons

- All atoms are generated from H (proton-proton chain) by nuclear reactions - *fusion*

  H fusion

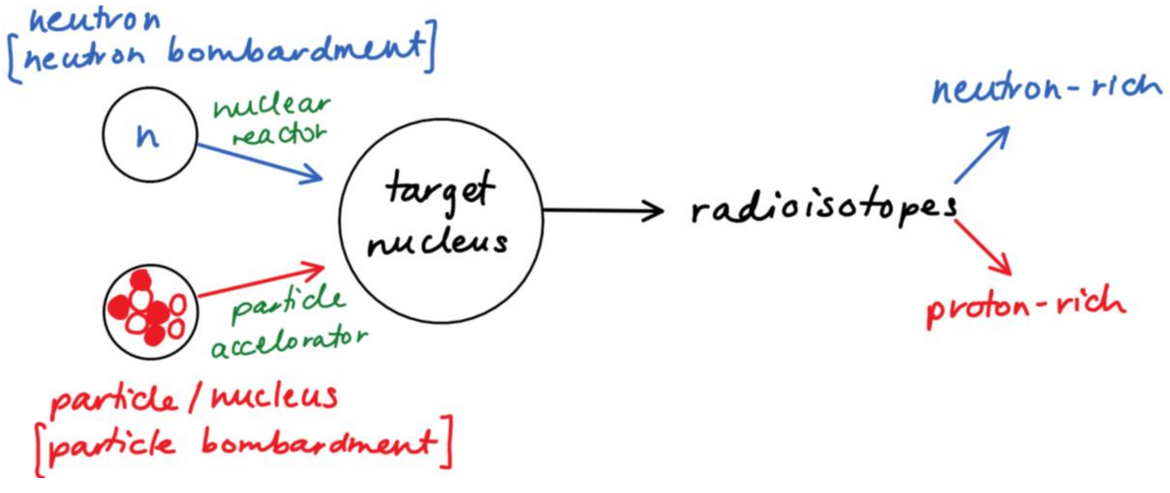
  $$4\,{}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2\,{}^{0}_{1}e + 2\gamma$$

  - Releases energy into surroundings as heat (exothermic) and radiation (neutrinos, $v$)
  - Energy releases comes from change in mass according to $E=mc^2$
- Z > 92 (i.e. beyond U) don't exist naturally on earth

e.g. technetium-99m

- m = metastable
- Formation: ${}^{99}_{42}Mo \rightarrow {}^{99m}_{43}Tc + {}^{0}_{-1}e$ (synthetic sources only)
- Arrangement of n+p in Tc-99m is very unstable
- Decay: ${}^{99m}_{43}Tc \rightarrow {}^{99}_{43}Tc + \gamma$ $t_{1/2}$ = 6 hours

⇒ Used in diagnostic imaging




Particle accelerators e.g. cyclotrons

- Electrostatic repulsion between nuclei must be overcome → accelerated to high velocities
- Produce radionuclides for medical uses