Lecture 2: Nuclear and Radiation Chemistry

- Natural Radioactivity

Lecture 3: Nuclear Stability, Decay Rates and Carbon Dating

Lecture 4: Biological effects of Radiation. Medical Imaging.
The composition of any nucleus is defined by two numbers.
- The **atomic number** is the number of protons in the nucleus.
  - This defines the chemical nature of the atom.
  - It is equal to the total charge on the nucleus.
- The **mass number** is the total number of nucleons (protons and neutrons) in the nucleus.

E.g. $^{12}_{6}C$ has an atomic number of 6 and a mass number of 12.

- A **nuclide** is an atom with a particular mass number and atomic number.
- Nuclides with the same atomic number but different mass numbers are called **isotopes**.
Nuclides and Isotopes

Nuclei with the same atomic number but different mass numbers are called **isotopes**.

E.g. Carbon may exist as a number of isotopes

- $^{11}\text{C}_6$: Unstable nucleus; prepared by nuclear reaction in a cyclotron.
- $^{12}\text{C}_6$: Stable nucleus; accounts for 98.89% of natural carbon.
- $^{13}\text{C}_6$: Stable nucleus; accounts for 1.11% of natural carbon.
- $^{14}\text{C}_6$: Unstable nucleus; trace amounts present in living matter.
- $^{15}\text{C}_6$: Unstable nucleus.
Nucleogenesis

Where do the elements come from?

How are atoms (nuclei) formed?

All atoms are generated from the simplest element, hydrogen $^1H$, by nuclear reactions.

Clouds of atomic hydrogen are pulled together by gravity and begin to heat as they are compressed. Eventually high enough temperatures for nuclear fusion are achieved and the cloud ignites as a star.
Nucleogenesis via Nuclear Fusion

The fundamental nuclear reaction is

\[ ^1H + ^1H \rightarrow ^2H + ^0e \]

This denotes a positron of mass 0 and charge 1.

In nuclear reactions, where the nuclide is changed, we must balance both the charge as well as the mass numbers.

In a nuclide, the charge is the same as the atomic number – the number of protons.
The fundamental nuclear reaction is

\[ ^1_1H + ^1_1H \rightarrow ^2_1H + ^0_1e \]

This is followed by two other nuclear reactions

\[ ^2_1H + ^1_1H \rightarrow ^3_2He + \gamma \]

This denotes high energy, short wavelength gamma radiation, which has no mass or charge.

and

\[ ^3_2He + ^1_1H \rightarrow ^4_2He + ^0_1e \]

Again note that both mass numbers and charges (atomic numbers) must balance.
Nucleogenesis

The overall reaction “hydrogen burning reaction”

\[
4_1^1H \rightarrow 4_2^4He + 2_1^0e + \gamma
\]

releases energy into the surroundings as heat (exothermic) and radiation.

As the star exhausts its hydrogen, it begins helium burning to fuse heavier nuclei to form increasingly larger atoms.

E.g.

\[
2_2^4He \rightarrow 8_4^8Be
\]

\[
4^8Be + 2_2^4He \rightarrow 12_6^6C
\]

Heavier nuclei like \( ^{13}C, ^{13}N, ^{14}N, ^{15}N, ^{15}O \ldots \) are produced by red giant stars, heavier nuclei in supergiants, and true heavy elements form in supernovae.
Nucleogenesis …and the periodic table

### H burning

- **1 H**
  - 1.008
- **2 H**
  - 2.012

### He burning

- **3 He**
  - 4.003

### C burning

- **4 C**
  - 12.01
- **5 N**
  - 14.01
- **6 O**
  - 16.00
- **7 F**
  - 19.00
- **8 Ne**
  - 20.18

### Red supergiant core

- **Na**
  - 22.99
- **Mg**
  - 24.31
- **Al**
  - 26.98
- **Si**
  - 28.09
- **P**
  - 30.97
- **S**
  - 32.07
- **Cl**
  - 35.45
- **Ar**
  - 39.95

### Supernova (everything heavier)

- **Supernova (everything heavier)**
Second-generation stars

Supernova explosions inject carbon, oxygen, silicon and other heavy elements up to iron into interstellar space. They are also the site where most of the elements heavier than iron are produced. This heavy element enriched gas will be incorporated into future generations of stars and planets.

We know from the presence of heavy elements in our sun that it is (at least) a second-generation star, currently undergoing hydrogen burning.

Without supernovae, the fiery death of massive stars, there would be no carbon, oxygen or other elements that make life possible.
Natural Radioactivity

Nucleogenesis produces nuclides that can be stable or unstable. Unstable nuclei decay through a range of mechanisms involving the release of particles with high kinetic energy or of $\gamma$-radiation. These high-energy products are collectively known as radioactivity.
Discovering Natural Radioactivity

Following Roentgen’s discovery of X-rays, Becquerel was trying to see if X-rays were present in solar radiation. He used one of his father’s fluorescent materials $\text{K}_2\text{UO}_2(\text{SO}_4)_2$ which turned out to emit a new penetrating radiation.

Henri Becquerel
Natural Radioactivity

The four most important radioactive decay mechanisms are

1. α decay
   
   e.g. \[ {^{212}_{83}Bi} \rightarrow {^{208}_{81}Tl} + {^2_4}\alpha \]

   The α particle is simply a helium nucleus with mass 4 and charge 2⁺.

   As with all nuclear reactions, both mass and charge are balanced.

2. β decay
   
   e.g. \[ {^5_12B} \rightarrow {^6_12C} + {^0_{-1}}e^- \]

   β (or β⁻) is an electron ejected from the nucleus.

   One neutron is changed into a proton in this nuclear reaction to balance the charge.
3. Positron ($\beta^+$) emission

When a positron ($\beta^+$) is ejected from the nucleus is usually collides with its antiparticle (the electron) in the surrounding environment very soon:

$$e^+ + e^- \rightarrow \gamma$$

e.g. $^{12}_7N \rightarrow ^{12}_6C + ^0_1e^+$

4. Electron capture

Electron capture is followed by emission of x-rays as electrons fall into lower energy states to fill the vacancy left by the captured electron.

(x-rays are not generally classified as radioactivity, although they can cause radiation damage.)

e.g. $^{55}_{26}Fe + ^0_{-1}e^- \rightarrow ^{55}_{25}Mn$
Balance the following nuclear decay reactions and identify the emitted particle where appropriate.

1. $^{234}_{92}U \rightarrow ^{230}_{90}Th + ^{4}_{2}He \text{ or } ^{4}_{2}\alpha$

2. $^{63}_{28}Ni \rightarrow ^{63}_{29}Cu + ^{0}_{-1}e^-$

3. $^{36}_{17}Cl + ^{0}_{-1}e \rightarrow ^{36}_{16}S$
Nuclear reactions are balanced in the same way, but may involve more than one reactant. Balance the following nuclear reactions and identify the missing nuclide or particle.

1. $^{14}_7 N + ^4_2 He \rightarrow ^{17}_8 O + ^1_1 H$ or $^1_1 p$

2. $^{239}_{94} Pu + ^4_2 He \rightarrow ^{242}_{96} Cm + ^1_0 n$

3. $^{28}_{14} Si + ^2_1 H \rightarrow ^{29}_{15} P + ^1_0 n$
Natural Radioactivity - $\gamma$ and x-rays

Both x-rays and $\gamma$ radiation are *high energy (= high frequency or short wavelength) forms of light*.

- x-rays have shorter wavelengths than visible or ultraviolet light - between 0.01nm and 10nm.
- $\gamma$ rays have very short wavelengths - less than 0.01nm or 0.1Å
Natural Radioactivity

Unstable heavy nuclei decay spontaneously by a series of steps through unstable intermediates. Over time, unstable nuclei give rise to a family of decay products in a decay series.

E.g. $^{238}\text{U}$ decays into...

\[
\begin{align*}
^{238}_{92}\text{U} & \longrightarrow ^{234}_{90}\text{Th} + ^4_2\alpha \\
^{234}_{90}\text{Th} & \longrightarrow ^{234}_{91}\text{Pa} + ^0_{-1}\beta \\
^{234}_{91}\text{Pa} & \longrightarrow ^{234}_{92}\text{U} + ^0_{-1}\beta \\
^{234}_{92}\text{U} & \longrightarrow ^{230}_{90}\text{Th} + ^4_2\alpha \\
^{230}_{90}\text{Th} & \longrightarrow ^{226}_{88}\text{Ra} + ^4_2\alpha
\end{align*}
\]

…etc, etc,…
Natural Radioactivity

A radioactive decay sequence (e.g. of $^{238}$U) can be represented more concisely as a graph of atomic number versus neutron number.

α decay is shown as a decrease of two protons ($Z$) and two neutrons ($N$).

β decay is shown as a decrease of one neutron and an increase of one proton.

Isotopes (same $Z$, different $N$) lie along vertical lines in this graph.
Natural Radioactivity

A radioactive isotope like $^{238}\text{U}$ thus generates a family of daughter isotopes in a decay series. Naturally-occurring uranium contains $^{238}\text{U}$, and so will also contain components of the decay series.
Radioactive Decay Series  ...and the periodic table
Nuclear Stability

What factors determine whether a nucleus is stable or unstable?

If we look at the range of stable nuclides that exist in nature, then there are two main observations:

1. The size of the nucleus.

2. The composition of the nucleus (proton:neutron)
Nuclear stability  1. Nuclear size

There are no stable nuclei heavier than $^{209}_{83}$Bi
Nuclear Stability 2. neutron:proton (N:Z)

All known stable nuclides fall inside the zone of stability. This zone has a N:Z ratio near to 1, but “bends” towards more neutrons per proton as the nucleus gets larger.

These two observations are enough to give us an empirical “rule” for nuclear stability that goes something like

“Unstable isotopes must decay towards the zone of stability, finally falling below $^{209}$Bi.”
Consider some of the known isotopes of carbon from the last lecture.

\[
\begin{align*}
{^{11}\text{C}}_6 & \quad \text{Unstable nucleus; } N/Z = 0.83 \quad \text{too low} \\
{^{12}\text{C}}_6 & \quad \text{Stable nucleus; } N/Z = 1 \\
{^{13}\text{C}}_6 & \quad \text{Stable nucleus; } N/Z = 1.17 \\
{^{14}\text{C}}_6 & \quad \text{Unstable nucleus; } N/Z = 1.33 \quad \text{too high} \\
{^{15}\text{C}}_6 & \quad \text{Unstable nucleus; } N/Z = 1.5 \quad \text{too high}
\end{align*}
\]
Nuclear Stability and Decay Mechanisms

Each nuclide decays *towards the zone of stability* by changing its N/Z ratio at constant mass number.

N/Z too low gives $\beta^+$ decay.

\[
\begin{align*}
\frac{11}{6}C & \rightarrow \frac{11}{5}B + \frac{0}{1}e^+ \\
N/Z &= 0.83 \quad N/Z = 1.2
\end{align*}
\]

Or equivalently by electron capture.

\[
\frac{55}{26}Fe + \frac{0}{-1}e^- \rightarrow \frac{55}{25}Mn
\]

N/Z = 1.11 \quad N/Z = 1.2

N/Z too high gives $\beta^-$ decay.

\[
\begin{align*}
\frac{14}{6}C & \rightarrow \frac{14}{7}N + \frac{0}{-1}e^- \\
N/Z &= 1.33 \quad N/Z = 1.0
\end{align*}
\]

\[
\begin{align*}
\frac{15}{6}C & \rightarrow \frac{15}{7}N + \frac{0}{-1}e^- \\
N/Z &= 1.5 \quad N/Z = 1.14
\end{align*}
\]
Nuclear Stability

The “rule” for nuclear stability:

“Unstable isotopes must decay towards the zone of stability, finally falling below $^{209}\text{Bi}$.”

Heavier nuclides than $^{209}\text{Bi}$ decay by a combination of mechanisms, using $\alpha$ decay to reduce mass (with $N/Z = 1$) and the other mechanisms to change $N/Z$. 

[Diagram showing neutron-proton (N/Z) versus proton (Z) with arrows indicating decay mechanisms for different isotopes.]

- Mass too high: $\alpha$ decay.
- N/Z too high: $\beta^-$ decay.
- N/Z too low: $\beta^+$ decay or electron capture.
Nuclear Stability

E.g. Here is how the $^{238}\text{U}$ decay sequence looks on our zone of stability graph.
The nuclear stability “rule” is *empirical*, based on the simple experimental observation of which nuclides are stable and which are not.

We can apply it like an *algorithm* to solve some nuclear decay problems, without understanding the reasons for nuclear stability.

To understand the reasons, the rule, and the observations, we need to consider the forces between nucleons within the nucleus.
Nuclear Stability - Origin of Decay Mechanisms

The stability of a nucleus involves the competition between two forces.

1. **Coulomb or electrostatic repulsion** between protons acts to push these nucleons apart over a long range.

2. The **strong nuclear force** is a short range attraction between all nucleons.

   This is the main function of neutrons in the nucleus. They contribute to the binding of the nucleus without also contributing to the electrostatic destabilisation.
Nuclear Stability - Origin of Decay Mechanisms

How does this explain our observations?

1. In nuclides with too few neutrons, the electrostatic repulsions overwhelm the strong nuclear attractions.

2. As the nucleus gets larger, the long-range electrostatic repulsion between protons accumulates and eventually overwhelms the strong nuclear attraction, even if N/Z is optimised.

This microscopic model does not explain how nuclides with too many neutrons can be unstable. To do so will involve quantum mechanics.
Summary

You should now be able to
• Recognise nuclear reactions, including the major spontaneous decay mechanisms.
• Calculate the average atomic mass from isotope information.
• Balance nuclear reactions.
• Determine decay mechanisms of nuclides.
• Describe factors involved in nuclear stability

Next Lecture

• Nuclear Fission and Human-Generated Radioactivity
• Decay Rates
  • How fast does an unstable nucleus decay?
  • Half-lives.
• Radiocarbon Dating