Nuclear Chemistry Notes

Isotopes: different forms of an element that have same number of protons and different number of neutrons.

Atomic Number: number of protons (found on Periodic Table)

Mass number: total number of neutrons and protons in a nucleus.
mass number = protons + neutrons
(mass number is not the same thing as the average atomic mass on the Periodic Table)

Isotope Notation: top number is **mass number**, bottom number is **atomic number**. See the oxygen examples below.

Isotopes Example:
Oxygen-16 and Oxygen-17 are different isotopes of oxygen. The numbers in those names are the mass numbers.
$^{16}_{8}O$ Oxygen-16 -Has 8 protons and 8 neutrons.
$^{17}_{8}O$ Oxygen-17 -Has 8 protons and 9 neutrons.
Both are oxygen (8 protons), but they have different numbers of neutrons and different mass numbers.

Important Nuclear Particles

$^{0}_{-1}e$ electron (beta, β)

$^{0}_{+1}e$ positron (anti-electron)

$^{1}_{0}n$ neutron

$^{4}_{2}He$ alpha (α) (a helium nucleus)

$^{0}_{0}\gamma$ gamma (gamma radiation a.k.a. gamma rays)

$^{1}_{1}p$ proton (same as $^{1}_{1}H$)

Nuclear Reactions
Nuclear reactions must follow two rules:
- Total **mass number** on reactant side must equal total mass number on product side
- Total **atomic number** on reactant side must equal total atomic number on product side

Example reaction:

$$^{240}_{95}\mathrm{Am} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{236}_{93}\mathrm{Np}$$

- The mass numbers (top numbers) add up to 240 on both sides of the arrow.
- The atomic numbers (bottom numbers) add up to 95 on both sides of the arrow.

Unlike regular chemical reactions, nuclear reactions feature elements changing into different elements. Therefore, the atom count for each element doesn't have to match between the reactant and product sides.

Types of Nuclear Reactions – Part 1 - Decay

Radioactive Decay:

- An unstable nucleus gives off a particle and (in most cases) becomes a new element.
- In decay reactions, the starting nucleus is always all by itself on the reactant side.
- There are multiple types of decay: alpha, beta, positron, gamma, and others.

Alpha Decay Example: (alpha decay of californium-252).

$^{252}_{98}\mathrm{Cf} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{248}_{96}\mathrm{Cm}$

- californium-252 is alone on the reactant side
- alpha particle ($^{4}_{2}\mathrm{He}$) is on the product side

Beta Decay Example: (beta decay of magnesium-27).

$^{27}_{12}\mathrm{Mg} \rightarrow {}^{0}_{-1}\mathrm{e} + {}^{27}_{13}\mathrm{Al}$

- magnesium-27 is alone on the reactant side
- beta particle ($^{0}_{-1}\mathrm{e}$) is on the product side
- atomic number adds up to 12 on both sides (careful not to do 12 = -1 + 11 = 10)

Gamma Decay Example: (gamma decay of iridium-192).

$^{192}_{77}\mathrm{Ir} \rightarrow {}^{0}_{0}\gamma + {}^{192}_{77}\mathrm{Ir}$

- iridium-192 is alone on the reactant side
- gamma particle ($^{0}_{0}\gamma$) is on the product side
- mass number and atomic number both stay the same for the original isotope
- The nucleus starts out in a higher energy, less stable state. After the decay reaction, it's more stable after losing some energy as gamma radiation.

Positron Decay Example: (positron decay of fluorine-16).

$^{16}_{9}\mathrm{F} \rightarrow {}^{0}_{+1}\mathrm{e} + {}^{16}_{8}\mathrm{O}$

- fluorine-16 is alone on the reactant side
- positron particle ($^{0}_{+1}\mathrm{e}$) is on the product side
- atomic number adds up to 9 on both sides
- atomic number changes in the opposite direction compared to a beta decay reaction

Other Types of Nuclear Reactions (Part 2)

Fusion:

- Two smaller nucleiu combine to form a bigger one
- Happens in stars
- Humans don't have the technology to use fusion in power plants (requires temperatures up to 100,000,000 °C)
- The most common fusion reactions involve combining hydrogen to produce helium

Example:

$^{2}_{1}\mathrm{H} + ^{3}_{1}\mathrm{H} \rightarrow ^{4}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n}$

- Two smaller isotopes on the left (hydrogen isotopes) combine to make a bigger one (helium) on the right

Fission:

- One large nucleus is split to form two smaller ones
- Often fission is started with a neutron on the reactant side
- Used in power plants and nuclear weapons (creates radioactive waste)
- The two most important nuclear fuels are $^{235}_{92}\mathrm{U}$ and $^{239}_{94}\mathrm{Pu}$

Example:

$^{239}_{94}\mathrm{Pu} + ^{1}_{0}\mathrm{n} \rightarrow ^{145}_{58}\mathrm{Ce} + ^{92}_{36}\mathrm{Kr} + 3\,^{1}_{0}\mathrm{n}$

- plutonium is split into smaller pieces (Ce and Kr)
- notice the "3" on the neutrons on product side: 3 neutrons means 3 mass units in your math

Bombardment

- Scientists bombard a nucleus with a smaller particle in a particle accelerator to produce new elements or do other types of research
- It is common to bombard an element with hydrogen and helium, but it is also possible to bombard any two nuclei together.
- The left side (reactants) will include this smaller particle, unlike a decay reaction
- Bombardment reactions can be classified as fusion reactions if a bigger nucleus is formed in the products

Example:

$^{14}_{7}\mathrm{N} + ^{4}_{2}\mathrm{He} \rightarrow ^{17}_{8}\mathrm{O} + ^{1}_{1}\mathrm{H}$

- Notice that the alpha particle (helium) is on the left side. Nitrogen is being bombarded by alpha particles.
- This is not alpha decay, because there are two particles on the reactant side.
- This reaction was done by a famous scientist (Ernest Rutherford) to demonstrate that a new isotope (oxygen-17, not usually found in nature) can be produced by bombarding nitrogen with alpha particles.

Electron Capture

- An unstable nucleus swallows up an electron from its own electron cloud.
- Electron is on the reactant (left) side of the equation
- This has the same effect on resulting atomic number as positron emission: atomic number goes down by 1

Example:

$^{38}_{20}\mathrm{Ca} + ^{0}_{-1}\mathrm{e} \rightarrow ^{38}_{19}\mathrm{K}$

- Notice that the electron is on the left side, unlike beta decay.

Strong Force / Neutrons / Nuclear Stability

Opposing Forces in the Nucleus:

1) Protons are all positively charged, so they repel each other due to the electromagnetic force.
2) Protons and neutrons are attracted by the **strong nuclear force**. This force holds the nucleus together.

Strong Force

- Only affects protons and neutrons
- Much stronger than the electromagnetic force (including Coulombic attraction / repulsion)
- Only an attractive force (no repulsion) – it holds particles together
- Only significant at very, very short distances, such as those found within the nucleus

Neutrons hold a nucleus together

- Neutrons experience the strong force (attractive)
- Neutrons have no charge, so they have no electromagnetic repulsion force
- Therefore, neutrons help the nucleus hold together despite the protons trying to push each other apart

Stable Number of Neutrons

- Small nuclei (calcium and smaller) need approximately equal numbers of protons and neutrons, or slightly more neutrons than protons.
  - Example 1: oxygen's most common isotope has 8 protons and 8 neutrons: equal numbers.
  - Example 2: fluorine's only stable isotope has 9 protons and 10 neutrons: one extra neutron.
- Most stable small nuclei have zero, one, or two extra neutrons (compared to their number of protons).

Not Enough Neutrons

- Elements bigger than helium always need at least as many neutrons as they have protons in order to be stable.
- If they have less neutrons than protons, they are likely to decay in one of the following ways:
  - positron emission (also known as positron decay)
  - electron capture

Example: **aluminum-25** (13 protons, 12 neutrons)
Since this isotope has less neutrons than protons, it will undergo positron emission as follows:

$${}^{25}_{13}\mathrm{Al} \rightarrow {}^{0}_{+1}\mathrm{e} + {}^{25}_{12}\mathrm{Mg}$$

- One of the protons has become a neutron in this decay reaction.
- The new isotope, magnesium-25, has 12 protons and 13 neutrons. This is approximately equal numbers with one extra neutron, which is a common arrangement for stable isotopes of smaller elements.
- The resulting isotope, magnesium-25, has a mass number close to the average atomic mass of Mg (24.31). This is one indication that the isotope has approximately a stable number of neutrons.

Too Many Neutrons

- Elements with too many neutrons tend to decay by **beta decay**. (Lone neutrons also decay by beta decay)
- In beta decay, one of the neutrons turns into a proton and emits an electron in the process. This increases the atomic number by one and improves the ratio of protons to neutrons.

Example: aluminum-29 (13 protons, 16 neutrons)
This isotope has three more neutrons than protons (too many), and for small elements this usually leads to beta decay:

$${}^{29}_{13}\mathrm{Al} \rightarrow {}^{0}_{-1}\mathrm{e} + {}^{29}_{14}\mathrm{Si}$$

- The resulting isotope, silicon-29, is a stable isotope with 14 protons and 15 neutrons.
- We now have an element with approximately equal numbers of protons and neutrons, with one extra neutron.
- The resulting isotope's mass number (29) is fairly close to the average atomic mass of the earth's silicon (28.09).