Nuclear Chemistry

Big Picture

Nuclear chemistry is the branch of chemistry that studies the atomic nuclei. Nuclei are held together with strong forces that overcome repulsion between like charges. Nuclear chemistry is based in the study of radioactive isotopes, which decay to form more stable elements. There are many different ways a radioactive isotope can release energy and become stable, and harnessing this energy can yield enormous amounts of power. In addition, radioactive decay can be used to estimate the ages of objects.

Key Terms

Nuclear Symbol: A way of describing a nuclear particle. The chemical symbol is written with the mass number on the left superscript and the atomic number on the left subscript.

Nuclide: The nucleus of a specific isotope.

Isotope: An element with a different number of neutrons.

Strong Nuclear Force: The attraction between protons at very close distances that help hold the nucleus together.

Nuclear Band of Stability: A zone where the ratio of neutrons to protons leads to a stable isotope.

Radiation: Energy emitted by decaying particles.

- **Alpha Radiation:** The release of a helium-4 nucleus (^4_2He) called an alpha (α) particle from an atom.
- **Beta Radiation:** The release of an electron called a beta (β) particle from an atom.
- **Gamma Radiation:** The release of a high-energy photon called a gamma (γ) ray from an atom.

Alpha Decay: Low-level radiation caused by the emission of alpha particles (helium nuclei ^4_2He)

Beta Decay: Medium-level radiation from the emission of beta particles (electrons).

Positron Emission: Medium-level radiation from the emission of a positron, which is the same as an electron, only with a positive charge, converting a proton into a neutron.

Electron Capture: When an atom takes in an electron, converting a proton into a neutron.

Fission: The splitting of an atomic nucleus into two or more smaller fragments.

Fusion: The combining of two atoms to form an element of a larger atomic number. Releases more energy than fission.

Chain Reaction: A self-sustaining fission process.

Critical Mass: The minimum quantity of a radioactive substance required for a chain reaction to occur.

Half-Life: The time it takes for half of a radioactive substance to decay.

Radioactive Dating: Measuring the amount of a naturally occurring radioactive isotope in an object and using its half-life to determine how old an object is.

Nuclear Symbol

The **nuclear symbol** is used to distinguish between the **nuclides** of different **isotopes**. The number of neutrons is equal to the difference between the mass number (superscript) and the atomic number (subscript).

mass number → 4
atomic number → 2
He ← chemical symbol

Nuclear Stability

The nucleus is the dense center of the atom that contains the positively charged protons and the neutral neutrons.

- The **strong nuclear force** holds the nucleus together.
- The stability of a nucleus depends on the ratio of neutrons to protons and on the overall size of the nucleus.
- As the number of protons in the nucleus increases, more neutrons are required to keep the nucleus stable.
  - Thus, what is initially a 1:1 ratio of neutrons to protons becomes 1.5:1 for larger atoms.
  - The **nuclear band of stability** shows the ratios of neutrons to protons for stable isotope.

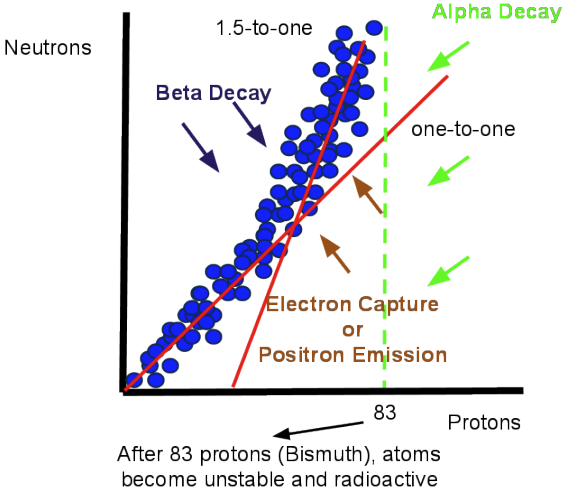


Figure: Nuclear Band of Stability
Image Credit: Rory Runser, CC-BY-SA 3.0

This guide was created by Steven Lai, Rory Runser, and Jin Yu. To learn more about the student authors, visit http://www.ck12.org/about/about-us/team/interns.

Disclaimer: this study guide was not created to replace your textbook and is for classroom or individual use only.

Nuclear Chemistry cont.

Radioactive Decay

Atoms outside of the nuclear band of stability will undergo some sort of decay in order to become more stable. All nuclei with 84 or more protons are radioactive and will emit particles to become more stable. Many elements with less than 84 protons have both stable and unstable isotopes.

Unstable nuclei emit **radiation** during radioactive decay. There are three main types of radiation:

- In **alpha radiation**, a helium-4 (${}^{4}_{2}\mathrm{He}$) nucleus called an alpha particle is emitted. It has the lowest energy and a low degree of penetration.
  - The alpha particle has a 2+ charge, but the electric charge symbol is usually omitted.
- In **beta radiation**, a fast-moving electron (${}^{0}_{-1}e$) called a beta particle is emitted. It has a medium level of energy and penetration power.
- In **gamma radiation**, a high-energy photon (γ) called a gamma ray is emitted. It has a high degree of penetration.
  - Gamma rays have no mass and no charge and are typically accompanies some other form of radiation.

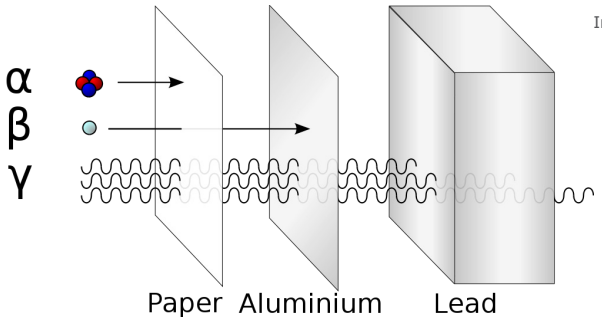


Image Credit: Ehamberg, CC-BY 2.5

Figure: Penetration of the three different types of radiation.

The type of radioactive decay a nucleus undergoes depends on the neutron to proton ratio.

- **Alpha decay** occurs when there are too many neutrons and protons for the nuclei to be stable.
  - Alpha emission increases the neutron to proton ratio–the mass number decreases by four and the atomic number decreases by two
  - Examples: ${}^{232}_{90}\mathrm{Th} \rightarrow {}^{228}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He}$, ${}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$
- **Beta decay** occurs when nuclei have too many neutrons relative to the number of protons
  - Beta emission increases the number of protons while decreasing the number of neutrons
  - Examples: ${}^{1}_{0}\mathrm{n} \rightarrow {}^{1}_{1}\mathrm{H} + {}^{0}_{-1}e$, ${}^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}e$
- **Positron emission** occurs when nuclei have too few neutrons relative to the number of protons.
  - A positron is like a positively charged electron.
  - Positron emission decreases the number of protons while keeping the mass number the same.
  - Example: ${}^{8}_{5}\mathrm{B} \rightarrow {}^{8}_{4}\mathrm{Be} + {}^{0}_{+1}e$
- **Electron capture** also occurs when nuclei have too few neutrons relative to the number of protons.
  - A proton is converted into a neutron and an electron is captured in the process.
  - Electron capture also decreases the number of protons while keeping the mass number the same.
  - Example: ${}^{59}_{28}\mathrm{Ni} + {}^{0}_{-1}e \rightarrow {}^{59}_{27}\mathrm{Co}$



A radioactive nucleus decays to become more stable. Often, a radioactive nucleus will undergo a series of decays before a stable nucleus is formed.

The nuclear equations for all of the examples are balanced. A nuclear equation is balanced if:

- The sum of the mass numbers (superscripts) on the left side of the equation equals to the sum of the mass numbers on the right
- The sum of the atomic numbers (subscripts) on the left side of the equation equals to the sum of the atomic numbers on the right

Radioactive decay results in transmutation, or the conversion of an atom of one element into an atom of a different element. Transmutation can occur naturally or artificially.

- All elements with atomic numbers above 92 are the result of artificial transmutation. They do not occur naturally and are synthesized in nuclear reactors and particle accelerators.

Nuclear Chemistry cont.

Applications of Nuclear Chemistry

Fission and Fusion

Fission

- Usually accomplished by bombarding a nucleus with a neutron
- Doesn't occur in the same way each time – can produce different products each time
- More neutrons, along with smaller nuclei, are released by the fission
  - These neutrons can react with other fission-able atoms, leading to a **chain reaction**
  - A **critical mass** is needed for the chain reaction to be self-sustaining; otherwise, the neutrons will escape without reacting

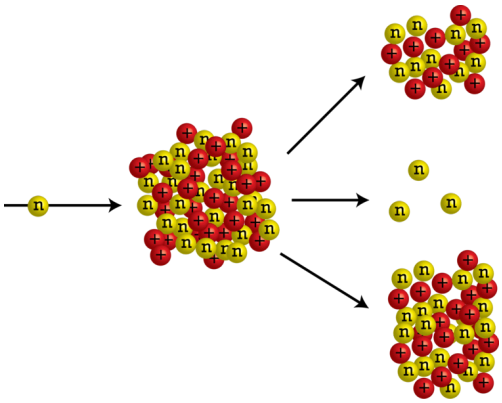


Image Credit: CK-12 Foundation CC-BY-NC-SA 3.0

- Releases large amounts of energy
  - When protons and neutrons combine to form a nucleus, mass is not conserved (occurs for all nuclear reactions, not just fission)
  - A very small amount of mass is lost and emitted as a large amount of energy
  - This energy is harnessed by nuclear plants
- Fissionable atoms include uranium-235 and plutonium-239

Fusion

- Releases more energy than fission reactions
- Requires very high temperatures
  - Stars like the sun have high enough temperatures for fusion to occur - the energy from the sun is a result of fusion



Despite the fact that both fission and fusion release energy, we can't take an atom and continually split and fuse it to produce energy. Iron (Fe, number 26) has the highest energy stored in its nucleus. Atoms larger than iron will release energy when they undergo fission, and atoms smaller than iron will release energy when they undergo fusion.

Half-Life and Radioactive Dating

Each isotope has a unique **half-life**. Half-lives can range from billions of years to millionths of a second.

- The half-life is the time for half of the nuclei in a sample to decay. Any given nucleus may or may not decay within that time.
- Nuclear reactions are not affected by the temperature, pressure, or surrounding molecules, and the half-life for an isotope cannot be increased or decreased.

Half-life is useful in **radioactive dating**.

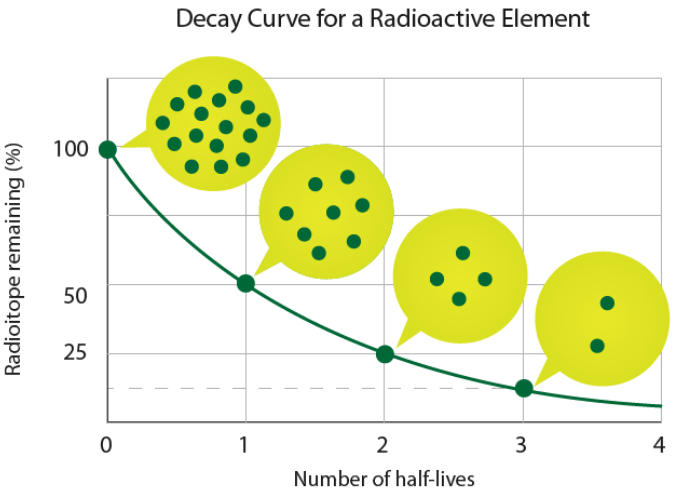


Image Credit: Jin Yu, CC-BY-NC-SA 3.0

- Some radioactive isotopes occur naturally.
- Measuring the amount of a naturally occurring radioactive isotope in an object and knowing its half-life can tell scientists how old an object is.
- For organisms, carbon-14 is a naturally occurring radioactive isotope. When the organism was alive, there was a fairly constant amount of carbon-14. When the organism died, carbon-14 stopped accumulating. Carbon-14 has a half-life of approximately 5,700 years. The amount of carbon-14 remaining can be used to determine how long ago the organism died.

Nuclear Chemistry Problem Guide

Common Problems

Balancing Nuclear Reactions

Just like chemical reactions, nuclear reactions need to be balanced, despite the fact that the law of conservation of mass does not apply. All energy released (or required) in a nuclear reaction comes from the energy between protons and neutrons in the nucleus. Below is a sample nuclear reaction, the decay of uranium-238 to thorium-234: ${}^{238}_{92}\mathrm{U} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{234}_{90}\mathrm{Th}$

Notice that the top numbers are conserved: 238 = 4 + 234. The bottom numbers are as well: 92 = 2 + 90.

Another example is the decay of carbon-14 into nitrogen-14: ${}^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\beta^{-}$

In this case, the bottom numbers add up (6 = 7 + -1), as do the top (14 = 0 + 14). The -1 on the bottom for the beta particle (β) is due to the fact that it has a negative charge.

Example: Balance the nuclear reaction of uranium-235 that is bombarded with a neutron, decaying into krypton-92 and barium-142.

1. Write out the parts of the equation that you know: ${}^{235}_{92}\mathrm{U} + {}^{1}_{0}n \rightarrow {}^{92}_{36}\mathrm{Kr} + {}^{142}_{56}\mathrm{Ba}$
2. Add up the top and bottom numbers on each side of the equation to determine what needs to be added.
   - Top: 235 + 1 = 236, 92 + 142 = 234
   - Bottom: 92 + 0 = 92, 36 + 56 = 92
3. The charges balance, but as mass of two daltons is needed on the left side of the equation. This is accomplished by adding two neutrons to the left side of the equation, indicating that this will form a chain reaction.
   ${}^{235}_{92}\mathrm{U} + {}^{1}_{0}n \rightarrow {}^{92}_{36}\mathrm{Kr} + {}^{142}_{56}\mathrm{Ba} + 2\,{}^{1}_{0}n$



DO NOT simplify this equation by removing one neutron from each side. In nuclear equations, it is important to leave the equation as is in order to display the result of neutron bombardments.

Half-Life Problems

- Calculate the amount of remaining nuclear substance after a given amount of time.

Example: The half-life of iodine-131 is 8 days. If a sample of pure iodine-131 weighs 50 grams, how much iodine-131 will remain after 24 days?

1. Calculate how many half-lives have occurred in the given time interaval.
   - 24 days • 1 half-life/8 days = 3 half-lives
2. The amount left is equal to the initial amount divided by 2^n, where n is the number of half-lives that have occurred.
   - 50 g/2^3 = 50 g/8 = 6.25 g of iodine-131

Carbon-Dating

Example: The half-life of carbon-14 is 5730 years. An object that originally had 80.0 grams of carbon-14 now has only 5.0 grams of carbon-14. How old is the object?

1. See how many half-lives have occurred. 80 g/ 2^n = 5.0 g, where n equals the number of half-lives.
   - Rearrange the equation to get , 80 g/5.0 g = 16 = 2^n so n = 4. Four half-lives have occurred.
2. Multiply the number of half-lives by the half-life.
   $4 \cdot 5730 \text{ years} = 22,920 \text{ years} \approx 23,000 \text{ years old}$

Notes