Chemistry 132 NT

Not everything that can be counted counts, and not everything that counts can be counted.

Albert Einstein

1

Chem 132 NT

Nuclear Chemistry

Module 1

Radioactivity and Nuclear Bombardment Reactions

- **Radioactivity**

The core of a nuclear reactor used in research.

2

Nuclear Chemistry

- In this chapter we will look at two types of **nuclear reactions**.
  - **Radioactive decay** is the process in which a nucleus spontaneously disintegrates, giving off radiation.
  - **Nuclear bombardment** reactions are those in which a nucleus is bombarded, or struck, by another nucleus or by a nuclear particle.

3

Radioactivity

- The phenomena of radioactivity was discovered by **Antoine Henri Becquerel** in 1896.
  - His work with uranium salts lead to the conclusion that the minerals gave off some sort of **radiation**.
  - This radiation was later shown to be separable by electric (and magnetic) fields into three types; **alpha** (α), **beta** (β), and **gamma** (γ) rays.

4

Radioactivity

- The phenomena of radioactivity was discovered by **Antoine Henri Becquerel** in 1896.
  - **Alpha rays** bend away from a positive plate indicating they are positively charged.
  - They are known to consist of **helium-4 nuclei** (nuclei with two protons and two neutrons).

5

Radioactivity

- The phenomena of radioactivity was discovered by **Antoine Henri Becquerel** in 1896.
  - **Beta rays** bend in the opposite direction indicating they have a negative charge.
  - They are known to consist of **high speed electrons**.

6

Radioactivity

- The phenomena of radioactivity was discovered by **Antoine Henri Becquerel** in 1896.
  - **Gamma rays** are unaffected by electric and magnetic fields.
  - They have been shown to be a form of **electromagnetic radiation** similar to x rays, but higher in energy and shorter in wavelength.

7

Nuclear Equations

- A **nuclear equation** is a symbolic representation of a nuclear reaction using nuclide symbols.
  - For example, the **nuclide symbol** for uranium-238 is

$$^{238}_{92}\text{U}$$

8

Nuclear Equations

- A **nuclear equation** is a symbolic representation of a nuclear reaction using nuclide symbols.
  - The radioactive decay of $^{238}_{92}\text{U}$ by alpha-particle emission (loss of a $^{4}_{2}\text{He}$ nucleus) is written

$$^{238}_{92}\text{U} \rightarrow \, ^{234}_{90}\text{Th} + \, ^{4}_{2}\text{He}$$

9

Nuclear Equations

- A **nuclear equation** is a symbolic representation of a nuclear reaction using nuclide symbols.
  - Reactant and product nuclei are represented in nuclear equations by their nuclide symbol.

10

Nuclear Equations

- A **nuclear equation** is a symbolic representation of a nuclear reaction using nuclide symbols.
  - Other particles are given the following symbols.

Proton	${}^{1}_{1}H$	**or**	${}^{1}_{1}p$
Neutron	${}^{1}_{0}n$		
Electron	${}^{0}_{-1}b$	**or**	${}^{0}_{-1}e$
Positron	${}^{0}_{1}b$	**or**	${}^{0}_{1}e$
Gamma photon	${}^{0}_{0}g$		

11

Nuclear Equations

- A **nuclear equation** is a symbolic representation of a nuclear reaction using nuclide symbols.
  - The total **charge is conserved** during a nuclear reaction.
  - This means that the **sum of the subscripts for the products must equal the sum of the subscripts for the reactants**.

12

Nuclear Equations

- A **nuclear equation** is a symbolic representation of a nuclear reaction using nuclide symbols.
  - The total **number of nucleons** is also conserved during a nuclear reaction.
  - This means that the **sum of the <u>superscripts</u> for the products must equal the sum of the <u>superscripts</u> for the reactants**.

Nuclear Equations

- A **nuclear equation** is a symbolic representation of a nuclear reaction using nuclide symbols.
  - Note that if all reactants and products but one are known in a nuclear equation, the identity of the missing nucleus (or particle) is easily obtained.
  - This is illustrated in the next example.

A Problem To Consider

- Technetium-99 is a long-lived radioactive isotope of technetium. Each nucleus decays by emitting one beta particle. What is the product nucleus?
  - The nuclear equation is

$$^{99}_{43}\mathrm{Tc} \rightarrow {}^{A}_{Z}\mathrm{X} + {}^{0}_{-1}\beta$$

  - From the superscripts, you can write

$$99 = A + 0, \quad \text{or} \quad A = 99$$

A Problem To Consider

- Technetium-99 is a long-lived radioactive isotope of technetium. Each nucleus decays by emitting one beta particle. What is the product nucleus?
  - The nucleus equation is

$$ {}^{99}_{43}\mathrm{Tc} \rightarrow {}^{A}_{Z}\mathrm{X} + {}^{0}_{-1}\beta $$

  - Similarly, from the subscripts, you get

$$ 43 = Z - 1, \quad \text{or} \quad Z = 43 + 1 = 44 $$

16

A Problem To Consider

- Technetium-99 is a long-lived radioactive isotope of technetium. Each nucleus decays by emitting one beta particle. What is the product nucleus?
  - The nuclear equation is

$$ {}^{99}_{43}\mathrm{Tc} \rightarrow {}^{A}_{Z}\mathrm{X} + {}^{0}_{-1}\beta $$

  - Hence A = 99 and Z = 44, so the product is

$$ {}^{99}_{44}\mathrm{Ru} $$

17

Nuclear Stability

- The existence of stable nuclei with more than one proton is due to the **nuclear force**.
  - The **nuclear force** is a strong force of attraction between nucleons that acts only at very short distances (about 10^{-15} m).
  - This force can **more than compensate** for the repulsion of electrical charges and thereby give a stable nucleus.

18

Nuclear Stability

- Several factors appear to contribute the stability of a nucleus.
  - The **shell model of the nucleus** is a nuclear model in which protons and neutrons exist in levels, or shells, analogous to the shell structure exhibited in electron configurations.
  - Experimentally, note that nuclei with certain numbers of protons and neutrons appear to be very stable.

19

Nuclear Stability

- Several factors appear to contribute the stability of a nucleus.
  - These numbers, called **magic numbers**, are the numbers of nuclear particles in a completed shell of protons or neutrons.
  - Because nuclear forces differ from electrical forces, these numbers are not the same as those for electrons is atoms.

20

Nuclear Stability

- Several factors appear to contribute the stability of a nucleus.
  - For protons, the magic numbers are

    2, 8, 20, 28, 50, and 82
  - For neutrons, the magic numbers are

    2, 8, 20, 28, 50, 82, and 126

21

Nuclear Stability

- Several factors appear to contribute the stability of a nucleus.
  - Evidence also points to the special stability of **pairs** of protons and **pairs** of neutrons.

22

Nuclear Stability

- Several factors appear to contribute the stability of a nucleus.
  - The table below lists the number of stable isotopes that have an even number of protons and an even number of neutrons.

	Number of Stable Isotopes			
	157	52	50	5
Number of protons	**Even**	**Even**	**Odd**	**Odd**
Number of neutrons	**Even**	**Odd**	**Even**	**Odd**

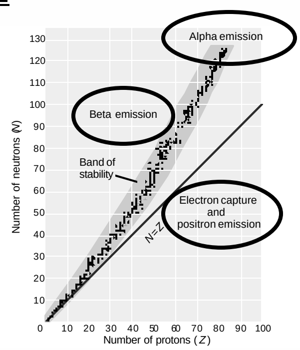
23

Nuclear Stability

- Several factors appear to contribute the stability of a nucleus.
  - Finally, when you plot each stable nuclide on a graph of protons vs. neutrons, these stable nuclei fall in a certain region, or **band**.
  - The **band of stability** is the region in which stable nuclides lie in a plot of number of protons against number of neutrons.

24

Band of Stability



25

Nuclear Stability

- Several factors appear to contribute the stability of a nucleus.
  - **No stable nuclides** are known with **atomic numbers greater than 83**.
  - On the other hand, all elements with Z equal to 83 or less have one or more stable nuclides.

26

A Problem To Consider

- One of the nuclides in each of the following pairs is radioactive; the other is stable. **Which is radioactive and which is stable**? Explain.

a) $^{208}_{84}\mathrm{Po}$, $^{209}_{83}\mathrm{Bi}$ b) $^{39}_{19}\mathrm{K}$, $^{40}_{19}\mathrm{K}$

(a) Polonium has an atomic number greater than 83, so $^{208}_{84}\mathrm{Po}$ **is radioactive.** Bismuth-209 has 126 neutrons (a magic number), so $^{209}_{83}\mathrm{Bi}$ **is expected to be stable.**

27

A Problem To Consider

- One of the nuclides in each of the following pairs is radioactive; the other is stable. **Which is radioactive and which is stable**? Explain.

  a) $^{208}_{84}\mathbf{Po}$, $^{209}_{83}\mathbf{Bi}$ b) $^{39}_{19}\mathbf{K}$, $^{40}_{19}\mathbf{K}$

(b) Of these two isotopes, $^{39}_{19}\mathbf{K}$ has a magic number of neutrons (20) so $^{39}_{19}\mathbf{K}$ **is expected to be stable.**

28

A Problem To Consider

- One of the nuclides in each of the following pairs is radioactive; the other is stable. **Which is radioactive and which is stable**? Explain.

  a) $^{208}_{84}\mathbf{Po}$, $^{209}_{83}\mathbf{Bi}$ b) $^{39}_{19}\mathbf{K}$, $^{40}_{19}\mathbf{K}$

(b) The isotope $^{40}_{19}\mathbf{K}$ has an odd number of protons (19) and an odd number of neutrons (21). Because stable odd-odd nuclei are rare, you would **expect** $^{40}_{19}\mathbf{K}$ **to be radioactive.**

29

Types of Radioactive Decay

- There are **six common types** of radioactive decay.
  - **Alpha emission** (abbreviated α): emission of a $^{4}_{2}$He nucleus, or alpha particle, from an unstable nucleus.
  - An example is the radioactive decay of radium-226.

$$^{226}_{88}\mathbf{Ra} \rightarrow {}^{222}_{86}\mathbf{Rn} + {}^{4}_{2}\mathbf{He}$$

30

Types of Radioactive Decay

- There are **six common types** of radioactive decay.
  - **Beta emission** (abbreviated β or β⁻): emission of a high speed electron from a stable nucleus.
  - This is equivalent to the conversion of a neutron to a proton.

$$ {}^{1}_{0}\mathrm{n} \text{ ® } {}^{1}_{1}\mathrm{p} + {}^{0}_{-1}\mathrm{e} $$

31

Types of Radioactive Decay

- There are **six common types** of radioactive decay.
  - **Beta emission** (abbreviated β or β⁻): emission of a high speed electron from a stable nucleus.
  - An example is the radioactive decay of carbon-14.

$$ {}^{14}_{6}\mathrm{C} \text{ ® } {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{b} $$

32

Types of Radioactive Decay

- There are **six common types** of radioactive decay.
  - **Positron emission** (abbreviated β^{+}): emission of a positron from an unstable nucleus.
  - This is equivalent to the conversion of a proton to a neutron.

$$ {}^{1}_{1}\mathrm{p} \text{ ® } {}^{1}_{0}\mathrm{n} + {}^{0}_{1}\mathrm{e} $$

33

Types of Radioactive Decay

- There are **six common types** of radioactive decay.
  - **Positron emission** (abbreviated β^+): emission of a positron from an unstable nucleus.
  - The radioactive decay of techencium-95 is an example of positron emission.

$$^{95}_{43}\mathrm{Tc} \circledR\, ^{95}_{42}\mathrm{Mo} + ^{0}_{1}\mathrm{e}$$

34

Types of Radioactive Decay

- There are **six common types** of radioactive decay.
  - **Electron capture** (abbreviated EC): the decay of an unstable nucleus by capturing, or picking up, an electron from an inner orbital of an atom.
  - In effect, a proton is changed to a neutron, as in positron emission.

$$^{1}_{1}\mathrm{p} + ^{0}_{-1}\mathrm{e} \circledR\, ^{1}_{0}\mathrm{n}$$

35

Types of Radioactive Decay

- There are **six common types** of radioactive decay.
  - **Electron capture** (abbreviated EC): the decay of an unstable nucleus by capturing, or picking up, an electron from an inner orbital of an atom.
  - An example is the radioactive decay of potassium-40.

$$^{40}_{19}\mathrm{K} + ^{0}_{-1}\mathrm{e} \circledR\, ^{40}_{18}\mathrm{Ar}$$

36

Types of Radioactive Decay

- There are **six common types** of radioactive decay.
  - **Gamma emission** (abbreviated γ): emission from an excited nucleus of a gamma photon, corresponding to radiation with a wavelength of about 10^{-12} m.
  - In many cases, radioactive decay produces a product nuclide in a **metastable** excited state.

37

Types of Radioactive Decay

- There are **six common types** of radioactive decay.
  - **Gamma emission** (abbreviated γ): emission from an excited nucleus of a gamma photon, corresponding to radiation with a wavelength of about 10^{-12} m.
  - The excited state is unstable and emits a gamma photon and goes to a lower energy state.

38

Types of Radioactive Decay

- There are **six common types** of radioactive decay.
  - **Gamma emission** (abbreviated γ): emission from an excited nucleus of a gamma photon, corresponding to radiation with a wavelength of about 10^{-12} m.
  - An example is metastable technetium-99.

$$^{99m}_{43}\mathrm{Tc} \rightarrow {}^{99}_{43}\mathrm{Tc} + {}^{0}_{0}\gamma$$

39

Types of Radioactive Decay

- There are **six common types** of radioactive decay.
  - **Spontaneous fission**: the spontaneous decay of an unstable nucleus in which a heavy nucleus of mass number greater than 89 splits into lighter nuclei and energy is released.
  - For example, uranium-236 undergoes spontaneous fission.

$$^{236}_{92}\text{U} \rightarrow\, ^{96}_{39}\text{Y} +\, ^{136}_{53}\text{I} + 4\,^{1}_{0}\text{n}$$

40

Predicting the Type of Radioactive Decay

- Nuclides **outside the band of stability** are generally **radioactive.**
  - Nuclides to the **left of the band** have more neutrons than that needed for a stable nucleus.
  - These nuclides tend to **decay by beta emission** because it reduces the neutron-to-proton ratio.

41

Predicting the Type of Radioactive Decay

- Nuclides **outside the band of stability** are generally **radioactive.**
  - In contrast, nuclides to the **right of the band** of stability have a neutron-to-proton ratio smaller than that needed for a stable nucleus.
  - These nuclides tend to **decay by positron emission or electron capture** because it increases the neutron to proton ratio.

42

Predicting the Type of Radioactive Decay

- Nuclides **outside the band of stability** are generally **radioactive.**
  - In the very **heavy elements**, especially those with Z greater than 83, radioactive decay is often by **alpha emission**.

A Problem To Consider

- Predict the expected type of radioactive decay for each of the following radioactive nuclides.

$^{47}_{20}\mathrm{Ca}$ $^{25}_{13}\mathrm{Al}$

  - The atomic weight of calcium is 40.1 amu, so you expect calcium-40 to be a stable isotope.
  - **Calcium-47** has a mass number greater than that of the stable isotope, so you would expect it to decay by **beta emission**.

A Problem To Consider

- Predict the expected type of radioactive decay for each of the following radioactive nuclides.

$^{47}_{20}\mathrm{Ca}$ $^{25}_{13}\mathrm{Al}$

  - The atomic weight of aluminum is 27.0 amu, so you expect aluminum-27 to be a stable isotope.
  - **Aluminum-25** has a mass number less than that of the stable isotope, so you would expect it to decay by **positron emission or electron capture**.

Operational Skills

- Writing a nuclear equation
- Deducing a product or reactant in a nuclear equation
- Predicting the relative stability of nuclides
- Predicting the type of radioactive decay

Time for a few review questions

46

47