Chapter 20: Nuclear Chemistry

Section 20.1: Nuclear Stability

Recall the definition of **isotopes**. "Isotopes are atoms that have the same atomic number (Z), but different mass numbers (A)".

For example: In the case of carbon, there are eight known isotopes.

$$\text{They are: } {}^{9}_{6}C \quad {}^{10}_{6}C \quad {}^{11}_{6}C \quad {}^{12}_{6}C \quad {}^{13}_{6}C \quad {}^{14}_{6}C \quad {}^{15}_{6}C \quad {}^{16}_{6}C$$

$$\text{Of these isotopes only two } {}^{12}_{6}C \text{ and } {}^{13}_{6}C \text{ are stable.}$$

Stability means that these isotopes do not decompose over time.

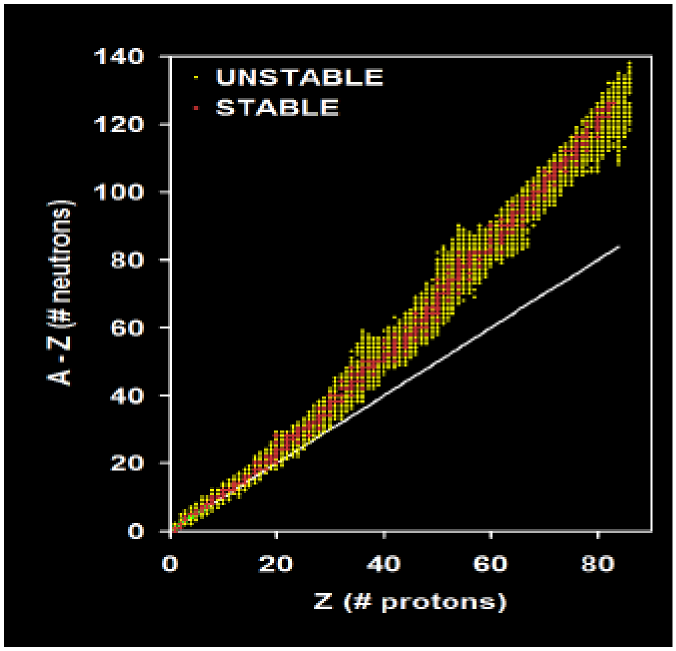
Note that three of the carbon nuclei are lighter than the stable nuclei. Here, "lighter" implies they have fewer neutrons than the stable nuclei, and, three nuclei are heavier than the stable nuclei. "Heavier" implies they have more neutrons than the stable nuclei.

The lightest and heaviest isotopes of an element are usually unstable. **Instability** means they spontaneously decompose into other nuclei.

Note that the word "isotopes" is used to refer to the group of atoms having same Z, but different A values. The word "**nuclide**" is used to refer to any one member of a group of isotopes.

Recall: the number of neutrons is calculated as: # neutrons = A-Z

The stability of a nucleus depends on its neutron to proton ratio or the Z/(A-Z) ratio.



The figure depicts a plot of the number of neutrons (A-Z) vs. the number of protons (Z). The red dots in the plot represent the stable nuclei. This is called the "**belt of stability**." The isotopes of light elements (i.e. elements with low Z) that fall in the belt of stability usually have a neutron to proton ratio close to 1.

This implies that the lightest and the heaviest isotopes of a given element (i.e. isotopes with the smallest and largest numbers of neutrons) fall outside the belt of stability and are unstable. This is often referred to as the "**sea of instability**".

We see that elements in the belt of stability with atomic numbers (Z) less than 20 have neutron to proton ratios close to 1. As the atomic number (Z) increases, the neutron to proton ratio increases.

Thus, the isotopes of heavier elements have a neutron to proton ratio greater than 1. Hence, heavier elements (i.e. Z > 20), whose isotopes lie in the belt of stability, have a neutron to proton ratio greater than 1.

$$\text{Consider the stable nuclide : } {}^{206}_{82}\text{Pb}$$

$$\text{\# neutrons} = 206 - 82 = 124$$

$$\text{and } \frac{\text{number of neutrons}}{\text{number of protons}} = \frac{124}{82} = 1.5$$

Unstable nuclides decompose by a process called **radioactive decay**. Unstable nuclides are said to be **radioactive** or to exhibit the property of **radioactivity**.

Section 20.2: Radioactivity

Unstable nuclei are called radioactive nuclei. The decomposition of a radioactive nucleus is called a radioactive decay. During radioactive decay, nuclei release a large amount of energy. About 300 radioactive nuclei, such as Uranium-238, occur in nature.
The vast majority of radioactive nuclei (about 2200) are too unstable to be found on earth but have been made in the laboratory. Radioactive nuclei that are prepared in the laboratory are typically obtained by bombarding stable nuclei with high-energy particles. Once a radioactive nucleus is prepared, it decomposes (or decays) releasing a large amount of energy.

Sections 20.3 - 20.4: Modes of Radioactive Decay

Any reaction leading to the change in composition of a nucleus is called a nuclear reaction. When a nuclide decays, it forms a different nuclide of lower energy. The excess energy during a nuclear reaction is emitted in the form of radiation. In a radioactive decay, the reactant nuclide is called the "**parent**", and, the product nuclide is called the "**daughter**".

Nuclides can decompose or decay in several ways. These ways are called **modes of decay**. In a nuclear reaction, the sum of the numbers of protons (Z) and the sum of the mass numbers (A) for the reactants must be equal to those for the products.

The most common modes of decay are:

1) Alpha Decay

This decay is characterized as the loss or the emission of an α-particle. An α-particle is a helium nucleus, that is the nucleus of helium-4. Thus, in a nuclear reaction involving α-decay, a helium-4 particle is emitted. Every element heavier than lead, Z = 82, exhibits α-particle emission. Very few lighter elements, Z < 82 exhibit α-particle emission.

Consider the nuclear reaction : $^{238}_{92}\text{U} \rightarrow {}^{4}_{2}\text{He} + ?$

In this reaction uranium-238 is the parent nuclide and helium-4 is an α-particle.
Recall: "In a nuclear reaction, the sum of the numbers of protons (Z) and the sum of the mass number (A) for the reactants must be equal to those for the products."

In order to find the daughter nuclide, we first need to find the atomic number (Z) of the daughter nuclide.

$$Z + 2 = 92$$

$$\text{Hence, } Z = 92 – 2 = 90$$

Now, look for the symbol of the element characterized by Z = 90 in the periodic table. The element is Thorium (Th).

Now, we balance the mass number (A).

$$238 = A + 4$$

$$\text{Hence, } A = 234$$

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

In this nuclear reaction Thorium-234 is the daughter nuclide.

2) Beta Decay

This decay is characterized by the loss or emission of a β-particle. A β-particle is a fast electron and is expressed by the symbol $^{0}_{-1}\beta$. For decays by emission of a β-particle, the product nuclide has the same number (A) as the reactant nuclide but an atomic number (Z) that is one unit higher than the reactant nuclide.

Consider the nuclear reaction: $^{14}_{6}\text{C} \rightarrow\, ^{0}_{-1}\beta + \,?$

In this reaction, $^{14}_{6}\text{C}$ is the parent nucleus and $^{0}_{-1}\beta$ is a β-particle.

Recall: "In a nuclear reaction, the sum of the number of protons (Z) and the sum of the mass numbers (A) for the reactants must be equal to those for the products." In order to find the daughter nuclide, we first determine the atomic number (Z).

$$^{14}_{6}\text{C} \rightarrow\, ^{0}_{-1}\beta + \,?$$

$$Z - 1 = 6$$

$$Z = 6 – (-1) = 7$$

Now, look for the symbol of the element characterized by Z = 7 in the periodic table. The element is Nitrogen (N).

$$^{14}_{6}C \rightarrow ^{0}_{-1}\beta + {}_{7}N$$

Since the mass number (A) is the same for parent and daughter nuclides in a radioactive decay by β-emission, the nuclear reaction is:

$$^{14}_{6}C \rightarrow ^{0}_{-1}\beta + ^{14}_{7}N$$

In this nuclear reaction, $^{14}_{7}N$ is the daughter nuclide.

3) Positron Decay

This decay is characterized by the loss or emission of a positron.
The positron is the antiparticle for the electron and has the symbol $^{0}_{1}\beta$.

Note: Every fundamental particle has a corresponding antiparticle. Particles and antiparticles have the same mass but opposite charge.

For positron decays, the product nuclide has the same mass number (A) as the reactant nuclide, but has an atomic number (Z), that is one unit lower than the reactant nuclide.

$$\text{Consider the nuclear reaction: } ^{40}_{19}K \rightarrow ^{0}_{1}\beta + ?$$

In this reaction $^{40}_{19}K$ is the parent nuclide and $^{0}_{1}\beta$ is a positron particle.

Recall: "In a nuclear reaction, the sum of the number of protons (Z) and the sum of the mass numbers (A) for the reactants must be equal to those for the products."

In order to find the daughter nuclide, we first need to determine the atomic number (Z).

$$^{40}_{19}K \rightarrow ^{0}_{1}\beta + ?$$

$$Z + 1 = 19$$

$$\text{Hence, } Z = 19 - 1 = 18$$

Now, look for the symbol of the element characterized by Z = 18 in the periodic table. The element is Argon, Ar.

$$^{40}_{19}K \rightarrow ^{0}_{1}\beta + {}_{18}Ar$$

Since the mass number (A) is the same for parent and daughter nuclides in a radioactive decay by positron emission, the nuclear reaction is:

$$^{40}_{19}K \rightarrow ^{0}_{1}\beta + ^{40}_{18}Ar$$

In this nuclear reaction, $^{40}_{18}Ar$ is the daughter nuclide.

4) Gamma Decay

This decay is characterized by the emission of high-energy photons, called γ particles or γ radiation.

The gamma particle has the symbol $^{0}_{0}\gamma$.

γ radiations have very short wavelengths and very high energies. Generally, γ emissions accompany the other types of decay discussed earlier, as well as other nuclear reactions.

For example: γ radiation is also produced when a particle and an antiparticle encounter each other and annihilate according to the reaction:

$$^{0}_{1}\beta + ^{0}_{-1}\beta \rightarrow 2\ ^{0}_{0}\gamma$$

Recall: $^{0}_{1}\beta$ is a positron and $^{0}_{-1}\beta$ is a β - particle.

Note: 2 γ indicates that two γ radiations with different wavelengths are emitted.

5) Electron Capture

Electron capture is often called K-electron capture. In this mode of decay, the electron from the innermost energy level of an atom falls into (is captured by) the nucleus of that atom. The innermost energy level is characterized by quantum number n = 1.

The electron has a symbol $^{0}_{-1}e$.

In the nucleus, there are protons and neutrons with symbols $^{1}_{1}p$ and $^{1}_{0}n$

The net effect of electron capture is the transformation of a proton to a neutron.

$$^{1}_{1}p + ^{0}_{-1}e \rightarrow ^{1}_{0}n$$

Consider a nuclear reaction in which an electron is captured:

$$^{82}_{37}\text{Rb} + \, ^{0}_{-1}\text{e} \rightarrow ?$$

In order to find the daughter nuclide, we first need to determine the atomic number (Z).

$$Z = 37 - 1 = 36$$

Now, look for the symbol of the element characterized by Z = 36 in the periodic table. The element is Krypton, Kr.

$$^{82}_{37}\text{Rb} + \, ^{0}_{-1}\text{e} \rightarrow \, ^{82}_{36}\text{Kr}$$

In Summary:

Mode of Decay	Symbol of particle emitted/captured
α emission	$^{4}_{2}\text{He}$
β emission	$^{0}_{-1}\beta$
positron emission	$^{0}_{1}\beta$
γ emission	$^{0}_{0}\gamma$
electron capture	$^{0}_{-1}\text{e}$
neutron emission	$^{1}_{0}\text{n}$

Memorize these.

In Section 20.4, practice the Interactive Problems.

Section 20.5: Bombarding Stable Nuclei with High Energy Particles

About 2000 radioactive nuclides have been prepared in the laboratory by bombarding stable nuclei. The bombarding particles may be:

1. neutrons
2. electrons
3. positrons
4. α-particles

Example: Consider the bombardment of a stable nuclide, Al-27, with neutrons.

$$^{27}_{13}Al + ^{1}_{0}n \rightarrow ^{28}_{13}Al$$

$$^{28}_{13}Al \text{ is a radioactive nuclide and it decays as :}$$

$$^{28}_{13}Al \rightarrow ^{0}_{-1}\beta + ^{28}_{14}Si \quad \text{This is an example of } \beta\text{ - decay.}$$

In 1935, Irene Curie and Frederick Joliet were the first to prepare radioactive isotopes in the laboratory. They bombarded stable Al-27 nuclei with high-energy α-particles.

$$^{27}_{13}Al + ^{4}_{2}He \rightarrow ^{30}_{15}P + ^{1}_{0}n$$

P-30 is radioactive and decays by emitting positron particles according to the reaction:

$$^{30}_{15}P \rightarrow ^{0}_{1}\beta + ^{30}_{14}Si$$

Sections 20.6 - 20.7: The Kinetics of Radioactive Decay

The radioactive decay is a first-order process.

Recall: For a first-order process

Rate = k [Reactant]

For radioactive nuclei, the rate of decay is called the "**activity**." Activity is represented by the symbol "A". Activity (A), is directly proportional to the number of radioactive nuclei.

Thus, $A \alpha N$ N = number of radioactive nuclei

$A = k N$ k = rate constant (or decay constant)

Hence, activity is the number of nuclei decaying per second, or the number of disintegrations per second. The SI unit of Activity is called the **Becquerel**. Becquerel is expressed with the symbol "Bq".

$$\text{Thus, mathematically} \quad 1\,Bq = \frac{1\,\text{disintegration}}{\text{second}} = \frac{1\,\text{nuclide}}{\text{second}}$$

Activity (A), can also be expressed using the **curie** unit (symbol "Ci"). 1 Ci is the number of disintegrations per second for 1.0 g of radium-226.

$$\text{Thus, mathematically} \quad 1\,\text{Ci} = \frac{3.7 \times 10^{10} \text{ disintegrations}}{\text{second}} = \frac{3.7 \times 10^{10} \text{ nuclides}}{\text{second}}$$

Since the radioactive decay is a first-order process, the integrated rate law for a radioactive decay is expressed as:

$$\ln \frac{N_o}{N} = kt$$

In this expression:

N_o = number of radioactive nuclei at t = 0.
N = number of radioactive nuclei which have not decayed or disintegrated by time "t".
k = rate constant.
t = time.

The expression for the half-life of a first-order process is:

$$t_{1/2} = \frac{0.693}{k}$$

Example: The half-life of Ra-226 is 1.60 x 10^3 yr.
(a) Calculate k in s^{-1}

$$t_{1/2} = 1.60 \times 10^3 \text{ yr.}$$

1 yr = 365 days 1 day = 24 hrs 1 hr = 3600 s.

$$\text{Thus, } t_{1/2} = 1.60 \times 10^3 \text{ year} \times \frac{365 \text{ days}}{\text{year}} \times \frac{24 \text{ hours}}{\text{day}} \times \frac{3600 \text{ s}}{\text{hour}} = 5.05 \times 10^{10} \text{ s}$$

The relationship between half-life and rate constant for a first-order process is:

$$t_{1/2} = \frac{0.693}{k}$$

$$k = \frac{0.693}{t_{1/2}} = \frac{0.693}{5.05 \times 10^{10} \text{ s}} = 1.37 \times 10^{-11} s^{-1}$$

$$k = 1.37 \times 10^{-11} s^{-1}$$

(b) Calculate the activity (A), in curies (Ci) of a 2.00 g sample of Ra-226.

$$\text{moles} = \frac{\text{mass (g)}}{\text{molar mass (g/mol)}}$$

$$= \frac{2.00\text{ g}}{226\text{ g/mol}} = 0.00885\text{ mol}$$

$$\text{N (\# nuclides)} = \frac{0.00885\text{ mol x }6.022\text{ x }10^{23}\text{ nuclides}}{\text{mol}} = 5.33\text{ x }10^{21}$$

Recall, A = k N

$$\text{or A} = \frac{1.37\text{ x }10^{-11}\text{s}^{-1}\text{ x }5.33\text{ x }10^{21}\text{ nuclides x }1\text{ Cu}}{3.70\text{ x }10^{10}\text{ nuclides/s}}$$

A = 1.97 Ci

In Section 20.7, practice the Interactive Problems.

Section 20.8: Dating by Radioactivity

Geologists, archeologists, and dendrochronologists use radioactive dating as a technique to date rocks, trees, and various artifacts. Earlier, we learned that there are eight isotopes for carbon.

Radiocarbon dating is based on the C-14 nuclide. C-14 is radioactive and decays, emitting β-particles.

The nuclear reaction is:

$$^{14}_{6}\text{C} \rightarrow {}^{0}_{-1}\beta + {}^{14}_{7}\text{N}$$

Carbon-14 is continuously produced in the atmosphere by the nuclear reaction

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

Over the years, the rates of these two reactions have become equal. Because of this the amount of carbon-14 in the atmosphere is almost constant. Carbon-14, along with other carbon isotopes, reacts with oxygen to form carbon dioxide.

Living plants consume carbon dioxide through photosynthesis. By this process, living plants consume carbon, including carbon-14. As long as a plant lives, its ratio of carbon-14 to carbon-12 is the same as the atmosphere.

However, when the plant dies, its ratio of carbon-14 to carbon-12 decreases. This decrease in the C-14/C-12 ratio is due to the radioactive decay of carbon-14. Remember that carbon-12 is stable and will not undergo any decay. The half-life of carbon-14 is 5730 years. Hence, the C-14/C-12 ratio decreases by half every 5730 years. Hence, by measuring the C-14/C-12 ratio in artifacts, scientists are able to date these objects.

Example: **An ancient piece of wood was analyzed. The analysis gave a decay rate for carbon-14 at 2.9 disintegrations per minute per gram of carbon. The decay rate of freshly cut wood is 12.6 disintegrations per minute per gram of carbon. Calculate the age of the ancient piece of wood.**

$$A = k\,N$$

The activity of the ancient wood is 2.9 disintegrations.$min^{-1}.g^{-1}$ at time t. The activity of the freshly cut wood is 12.6 disintegrations.$min^{-1}.g^{-1}$ at time t = 0 (initial time).

Radioactive decay is a first-order process, hence,

$$A_o = k\,N_o$$

$$\frac{A_o}{A_t} = \frac{k\,N_o}{k\,N_t}$$

$$\frac{12.6\ \text{disintegrations.min}^{-1}.\text{g}^{-1}}{2.9\ \text{disintegrations.min}^{-1}.\text{g}^{-1}} = \frac{N_o}{N_t} \qquad \frac{N_o}{N_t} = 4.3$$

$$\ln\frac{N_o}{N_t} = k\,t$$

$$\text{The half-life } (t_{1/2}) \text{ of } {}^{14}_{6}\text{C is 5730 years.}$$

$$t_{1/2} = \frac{0.693}{k}$$

$$k = \frac{0.693}{5730\ yr} = 1.21 \times 10^{-4}\ yr^{-1}$$

$$\ln \frac{N_o}{N_t} = k\,t$$

$$\ln 4.3 = 1.21 \times 10^{-4}\ yr^{-1} \times t$$

$$1.46 = 1.21 \times 10^{-4}\ yr^{-1} \times t$$

$$t = \frac{1.46}{1.21 \times 10^{-4}\ yr^{-1}} = 12100\ yr$$

The age of the ancient piece of wood is 12,100 years.

Section 20.9: Detection of Radioactivity

The two most common instruments used to measure radioactivity are:

(1) the Geiger-Müller Counter
(2) the Scintillation Counter

(1) **Geiger-Müller counters** are commonly called Geiger counters. The probe of a Geiger counter is filled with argon gas. The highly energetic particles emitted by decaying radioactive nuclei collide with the argon atoms. These collisions result in the formation of Ar^+ ions.

$$Ar_{(g)} + \text{Particles} \rightarrow Ar^+_{(g)} + e^- + \text{Particles}$$

The electrons generate a current which is recorded as counts per unit time.

(2) The **scintillation counter** uses a photo cell to measure the number of counts per unit time. The counter contains chemicals that give off light when they undergo collisions with the high-energy particles emitted by the radioactive nuclei. These flashes of light are measured as counts.

Section 20.10: The Mass Defect

The energy released during a nuclear reaction is generally much larger than that released during a chemical reaction. Why is that so?

A nuclear reaction is characterized by a change in the number of neutrons and protons in the participating nuclei. The nuclear forces binding neutrons and protons are much stronger forces than the Coulombic forces binding electrons to nuclei.

Hence, changing the number of neutrons and protons in a nucleus involves much larger energies than changing the location of electrons during a chemical reaction.

How can we predict the energy released during a nuclear reaction?

First, recall the well known equation discovered by Albert Einstein.

$$E = m c^2$$

E is the energy of a particle or nuclide of mass, m.

c is the speed of light in vacuum ($c = 3 \times 10^{8}$ m/s).

In nuclear reactions, unlike in chemical reactions, the mass is not conserved (i.e. the mass of products differs from the mass of reactants). The difference in mass between products and reactants, Δm is called the **mass defect**. Hence, the change in the energy for the reaction (ΔE) is related to the change in the mass, (Δm) by the equation:

$$\Delta E = \Delta m\, c^2$$

Consider the formation of a ${}^{16}_{8}O$ nucleus from 8 neutrons and 8 protons.

$$\text{The reaction is:} \quad 8\,{}^{1}_{0}n + 8\,{}^{1}_{1}H \rightarrow {}^{16}_{8}O$$

$$\text{The mass of each component is} \quad {}^{1}_{0}n = 1.67493 \times 10^{-24}\text{ g}$$

$${}^{1}_{1}H = 1.67262 \times 10^{-24}\text{ g} \qquad {}^{16}_{8}O = 2.65535 \times 10^{-23}\text{ g}$$

Note: This is the mass of one ${}^{16}_{8}O$ nucleus.

Δm = change in mass

$$\Delta m = \text{mass}_{\text{(products)}} - \text{mass}_{\text{(reactants)}}$$

$$\text{mass}_{\text{(products)}} = 2.65535 \times 10^{-23}\text{ g}$$

$$mass_{(products)} = 8 \times (1.67493 \times 10^{-24}) + 8 \times (1.67262 \times 10^{-24})$$

$$= 2.67804 \times 10^{-23} \text{ g}$$

$$\Delta m = 2.65535 \times 10^{-23} \text{ g} - 2.67804 \times 10^{-23} \text{ g}$$

$$\Delta m = - 2.269 \times 10^{-25} \text{ g}$$

This is the change in mass for the formation of one nucleus of $^{16}_{8}O$.

Recall Avogadro's Number: 1 mol of nuclei contains 6.022×10^{23} nuclei

$$\Delta m = - 2.269 \times 10^{-25} \frac{\text{g}}{\text{nucleus}} \times 6.022 \times 10^{23} \frac{\text{nuclei}}{\text{mol}}$$

$$\Delta m = - 0.1366 \text{ g/mol}$$

This means that a mass of 0.1366 g would be "lost" if 1 mole of oxygen-16 nuclide was made from 8 moles of neutrons and 8 moles of protons. This is called **the mass defect**.

This occurs because the nuclear mass of one oxygen-16 nuclide is less than the combined masses of 8 neutrons and 8 protons.

Note, the mass is not really "lost". It is simply transformed into energy, since $E = m c^2$

Sections 20.11 - 20.12: Mass - Energy Relations

The energy change accompanying a nuclear reaction can be calculated using the Einstein equation:

$$\Delta E = \Delta m c^2$$

In this equation:

ΔE = change in energy i.e. $\Delta E = energy_{(products)} - energy_{(reactants)}$

Δm = change in mass i.e. $\Delta m = mass_{(products)} - mass_{(reactants)}$

c = speed of light = 3.00×10^{8} m/s

Substituting the value of c in this equation, we get:

$\Delta E = \Delta m \times (3.00 \times 10^8 \text{ m/s})^2$

$\Delta E = \Delta m \times (9.00 \times 10^{16} \text{ m}^2/\text{s}^2)$

Recall: Energy is expressed in joules (J) 1 J = 1 kg. m^2/s^2

Hence, 1 m^2/s^2 = 1 J/kg

$\Delta E = \Delta m \times 9.00 \times 10^{16}$ J/kg

Note that Δm, *the change in mass, is often expressed in grams. You need to remember to convert gram (g) to kilogram (kg).*

Example: Calculate ΔE in kJ/mol for the nuclear reaction:

	$^{230}_{90}\text{Th} \rightarrow$	$^{4}_{2}\text{He}$ +	$^{226}_{88}\text{Ra}$
Atomic mass (g/mol)	230.0332	4.00260	226.02544

$$\Delta E = \Delta m\, c^2$$

where $c^2 = 9.00 \times 10^{16}$ J/kg

$$\Delta m = m_{\text{(products)}} - m_{\text{(reactants)}}$$

$m_{\text{(products)}}$ = 1 mol x 4.00260 g/mol + 1 mol x 226.02544 g/mol

$m_{\text{(products)}}$ = 230.02804 g

$m_{\text{(reactants)}}$ = 1 mol x 230.0332 g/mol = 230.0332 g

Δm = 230.02804 g – 230.0332 g $\qquad \Delta m$ = - 0.00516 g

A nuclear reaction is accompanied by a very large change in energy!

Δm = - 0.00516 g $\qquad c^2 = 9.00 \times 10^{16}$ J/kg

$$\Delta E = 0.00516 \text{ g} \times \frac{1 \text{kg}}{1000 \text{ g}} \times 9.00 \times 10^{16} \frac{\text{J}}{\text{kg}}$$

$$= -4.6 \times 10^{11} \text{ J}$$

$$\text{In kJ} \quad = -4.6 \times 10^{11} \text{ J} \times \frac{1 \text{kJ}}{1000 \text{ J}}$$

$$= -4.6 \times 10^{8} \text{ kJ}$$

Thus, the amount of energy released is 4.6×10^{8} kJ.

In Section 20.12, practice the Interactive Problems.

Section 20.13: Nuclear Binding Energy

Consider the nuclear reaction in which a carbon-14 nucleus is broken down into its constituent neutrons and protons.

$$^{14}_{6}C \rightarrow 8\ ^{1}_{0}n + 6\ ^{1}_{0}p$$

The change in energy, ΔE, associated with the breaking down of one carbon-14 nucleus is called the **nuclear binding energy**. The change in energy, ΔE, is expressed by Einstein's equation:

$$\Delta E = \Delta m\ c^2$$

Δm is the difference in mass between the constituent neutrons and protons and the nucleus. Nuclear scientists express binding energies with the unit of **electron Volts (eV)** instead of kJ or J.

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$$

Nuclei have binding energies in the range of millions of electron Volts. Hence, the term **Mega electron Volts** (**MeV**) is more appropriate than electron Volts.

$$1 \text{ MeV} = 1 \times 10^{6} \text{ eV}$$
$$1 \text{ MeV} = 1.602 \times 10^{-13} \text{ J}$$

Section 20.14: Nuclear Fission

Heavy elements undergo fission when bombarded by neutrons. Isotopes of two elements, namely, U-235 and Pu-239, undergo fission with relatively low energy neutrons.

For example: Consider the bombardment of one mole of uranium-235 with one mole of neutrons.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\ ^{1}_{0}n$$

A U-235 nuclide can actually undergo fission to form different products.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{87}_{35}Br + ^{146}_{57}La + 3\,^{1}_{0}n$$

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{72}_{30}Zn + ^{160}_{62}Sm + 4\,^{1}_{0}n$$

More than several hundred isotopes of 35 elements have been identified as fission products of U-235. The U-235 nuclide corresponds to 0.7% of naturally occurring uranium. The more abundant isotopes of uranium do not undergo fission.

For every neutron consumed in these fission reactions, 3 to 4 neutrons are produced. This process is called a chain reaction. The rate of a chain reaction increases exponentially with time.

Thus, fission reactions are self-sustained reactions. For a fission reaction to sustain itself at the same level, a critical mass of radioactive material is required. If less than the critical mass of radioactive material is present, then the reaction is said to be subcritical. Subcritical reactions die out.

However, if more than the critical mass of radioactive material is present, then the reaction is described as supercritical. In a supercritical process, heat builds up to such an extent that it results in a violent explosion.

Recall Einstein's Equation: $\Delta E = \Delta m\, c^2$

The energy released in the fission process is directly related to the decrease in mass. For every gram of U-235 that undergoes fission, approximately 80 million kJ of energy is released.

Section 20.15: Nuclear Fission Reactors

Much of energy research and development has been based upon the assumption that nuclear power would fill the gap between growing energy demands and dwindling fossil fuel supplies. We know that fission processes provide a large amount of energy. Currently, the reaction used in most nuclear reactors is:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\,^{1}_{0}n$$

In this reaction, high energy and high velocity neutrons are produced. These neutrons must be slowed down to cause more U-235 to undergo fission. Substances that can reduce the energy of neutrons are called moderators.

Moderators are made of light elements like carbon, hydrogen or oxygen. Water is often used as a moderator.

Secondly, the number of neutrons needs to be regulated. Look at the equation describing this nuclear reaction. For every mole of U-235, only one mole of neutrons is needed. The number of neutrons is reduced by cadmium control rods. The control rods absorb the neutrons produced by the fission reaction,

A cooling system is provided to absorb the heat generated by the nuclear reaction. This heat is transferred away from the reaction site to perform useful work. Most reactors use water as a coolant. This is because water has high thermal conductivity and a large heat capacity.

In order to prevent neutrons, γ-rays and other radiation from escaping the reactor, the reactor is shielded. The shielding is often made of concrete mixed with lead salts which absorb radiation.

Finally, a containment vessel surrounds all portions of the reactor. The containment vessel does not allow radioactive material to escape.

Three types of reactors are commonly used in nuclear power plants:

(1) Light water reactors
(2) High temperature gas-cooled reactors
(3) Breeder reactors

Section 20.16: Nuclear Fusion

A second method that may be used to obtain energy from nuclear reactions is to fuse two or more light nuclei together to form a heavier element. The combination of hydrogen nuclei in the sun is one example of nuclear fusion.

$$\text{The hydrogen fusion reaction is written as: } {}^{2}_{1}\text{H} + {}^{2}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He}$$

Unfortunately, this fusion process has a very high activation energy (E_a).

$${}^{2}_{1}\text{D} + {}^{2}_{1}\text{D} \rightarrow {}^{4}_{2}\text{He} + {}^{1}_{0}\text{n}$$

$${}^{2}_{1}\text{D} + {}^{3}_{1}\text{T} \rightarrow {}^{4}_{2}\text{He} + {}^{1}_{0}\text{n}$$

where ${}^{2}_{1}\text{D}$ and ${}^{3}_{1}\text{T}$ are isotopes of hydrogen called deuterium and tritium. These two reactions have low activation energies and show some promise for controlled fusion power plants.