REVIEW: TOPIC 10

NAME: ____________

DUE: ____________

UNIT 10 – MAJOR UNDERSTANDINGS

- ☆ 3.1o Stability of an isotope is based on the ratio of neutrons and protons in its nucleus. Although most nuclei are stable, some are unstable and spontaneously decay, emitting radiation.
- ☆ 4.4a Each radioactive isotope has a specific mode and rate of decay (half-life).
- ☆ 5.3a A change in the nucleus of an atom that converts it from one element to another is called transmutation. This can occur naturally or can be induced by the bombardment of the nucleus with high-energy particles.
- ☆ 3.1p Spontaneous decay can involve the release of alpha particles, beta particles, positrons, and/or gamma radiation from the nucleus of an unstable isotope. These emissions differ in mass, charge, ionizing power, and penetrating power.
- ☆ 4.4b Nuclear reactions include natural and artificial transmutation, fission, and fusion.
- ☆ 4.4f There are benefits and risks associated with fission and fusion reactions.

UNIT 10 – MAJOR UNDERSTANDINGS (CONTINUED)

- ☆ 4.4c Nuclear reactions can be represented by equations that include symbols which represent atomic nuclei (with mass number and atomic number), subatomic particles (with mass number and charge), and/or emissions such as gamma radiation.
- ☆ 5.3b Energy released in a nuclear reaction (fission or fusion) comes from the fractional amount of mass that is converted into energy. Nuclear changes convert matter into energy.
- ☆ 5.3c Energy released during nuclear reactions is much greater than the energy released during chemical reactions.
- ☆ 4.4e There are inherent risks associated with radioactivity and the use of radioactive isotopes. Risks can include biological exposure, long-term storage and disposal, and nuclear accidents.
- ☆ 4.4d Radioactive isotopes have many beneficial uses. Radioactive isotopes are used in medicine and industrial chemistry for radioactive dating, tracing chemical and biological processes, industrial measurement, nuclear power, and detection and treatment of diseases.

NUCLEAR CHEM.

INTRODUCTION

Isotopes of atoms can be stable or unstable. Stability of isotopes is based on the number of protons and neutrons in an atom's nucleus. Some nuclei are unstable and spontaneously decay, emitting radiation.

A – HALF-LIFE

The half-life of a radioactive isotope is the time required for one-half of the nuclei of a given sample of that isotope to disintegrate. The decay of radioactive elements occurs erratically, so that a small amount might decay one day and a large amount might decay the following month. Scientists, knowing that the mass of an atom is essentially derived from its nucleus, have picked a span of time in which half of the mass of the sample has decayed.

Sample Problem:

If the half-life of the isotope ^{42}K is 12.4 hours, and if you had 100 grams of the isotope, how much would you have left after 37.2 hours?

Solution:

Divide the total time by $\frac{\textbf{37.2 hours}}{\textbf{12.4 hours}}$ = **3 half-life periods**

During the first half-life period, the following would occur: **100 g → 50.0 g**

During the second half-life period, the following would occur: **50 g → 25.0 g**

During the third half-life period, the following would occur: **25 g → 12.5 g**

Answer: **12.5 grams**

Note: It is strongly suggested that you should know the definition for half-life and then use your own good reasoning power, instead of using equations or formulas, to solve such problems.

B – Natural Radioactivity

Radioactivity is the spontaneous disintegration of the nucleus of an atom with the emission of particles and/or radiant energy. Some naturally occurring elements are radioactive. Therefore, the term **natural radioactivity** is used.

When the nucleus of an element contains a disproportionate amount of neutrons, as compared to protons, the nucleus starts to emit particles. It is then classified as radioactive. Elements with an atomic number of higher than 82 (Lead) fall into this category. When one element is changed to another element because of change in the nucleus, the change is called **transmutation**.

Difference in Emanations

Emanations differ from each other in mass, charge, penetrating power, and ionizing power. The nuclear disintegration of naturally radioactive atoms produces alpha particles, beta particles and gamma radiation.

Alpha decay – When an alpha particle is given off as the result of nuclear disintegration, the reaction is called alpha decay. Alpha particles can be considered helium nuclei because they consist of 2 protons and 2 neutrons. Therefore, they have a mass of four **amu** (atomic mass unit). An atom that emits an alpha particle is called an **alpha emitter**.

When an atom emits an alpha particle, the atomic number is reduced by 2 and the mass number is reduced by 4.

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

Beta decay – Beta particles are high-speed electrons. When a beta particle is given off as the result of neutron disintegration, the reaction is called beta decay. The atom that emits a beta particle is called a **beta emitter**.

When an atom emits a beta particle, the atomic number is increased by 1 and the mass number remains the same.

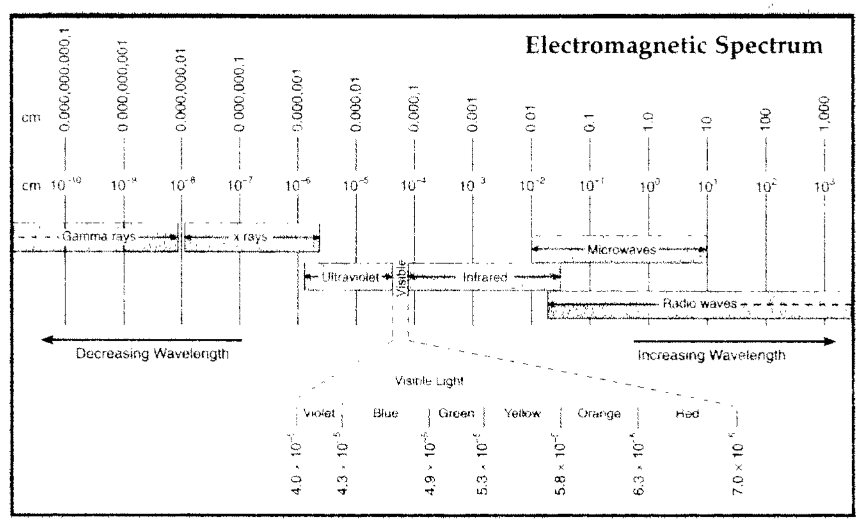
Example: $^{234}_{90}Th \rightarrow ^{234}_{91}Pa + ^{0}_{-1}e$

Gamma radiation – Gamma rays are not particles and do not have mass or charge. They are similar to high energy X-rays. Most nuclear changes involve the emission of gamma rays, reducing the energy content of the nucleus without affecting its charge or mass. The detection and study of radioactivity is made possible by its ionizing, fluorescent, and photographic effects.

Separation of emanations is possible by an electric field or magnetic field. In such an electric field, alpha particles are deflected toward the negative electrode, beta particles toward the positive electrode, but gamma rays are not affected by the field.

Real World Connections
Electromagnetic Spectrum

The electromagnetic spectrum includes the entire range of radiation – extending in frequency from approximately 10^{23} hertz to 0 hertz or, in corresponding wavelengths, from 10^{-13} centimeter to infinity. The forms of radiation include (in order of decreasing frequency) cosmic-ray photons, gamma rays, X-rays, ultraviolet radiation, visible light, infrared radiation, microwaves, and radio waves.



C – Artificial Radioactivity

Natural radioactivity occurs under natural conditions and results in natural transmutation. The products of natural transmutation are radioactive isotopes, which decay finally into a stable isotope of lead. However, elements can be made radioactive by bombarding their nuclei with high energy particles such as protons, neutrons, and alpha particles producing man-made elements. When the element nitrogen, for example, is bombarded by alpha particles, the nuclear reaction that takes place is:

alpha particle + nitrogen → proton + oxygen

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

As noted from the above reaction, isotopes of two new elements are formed. This is called **artificial transmutation.** The process includes the bombardment of nuclei by accelerated particles which cause nuclei to become unstable and may result in the formation of radioactive isotopes, or radioactive isotopes of new elements called **radioisotopes**. Another example follows:

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

In the both of the above equations, note the following:

- The sum of the atomic masses (the superscripts) on the left must equal the total of atomic masses (the superscripts) on the right.
- The sum of the atomic numbers (the subscripts) on the left must equal the total of the atomic numbers (the subscripts) on the right.
- In an equation depicting artificial radioactivity, there are at least two reactants on the left side of the equation. In natural radioactivity equations, there appears only one reactant on the left side of the equation. The following example points out how the above suggestions work.

Problem: In the following reaction what nucleus is represented by ***X***?

$$X + ^{1}_{1}H \rightarrow ^{6}_{3}Li + ^{4}_{2}He$$

Solution: Noting that the sums of both superscripts of the completed right side of the equation are 10 and 5, respectively, and the sums on the incomplete left side are 1 and 1, respectively, the atomic mass and number of element ***X*** can be easily determined.

Since the atomic number identifies the element, this element with an atomic number of 4 is Beryllium, which has an atomic mass of 9.

Therefore, the answer is written (at right): $^{9}_{4}X = ^{9}_{4}Be$

Accelerators – Accelerators are used to give charged particles sufficient kinetic energy to overcome electrostatic forces and penetrate the nucleus. Electric and magnetic fields are used to accelerate these charged particles.

D – Nuclear Energy

In nuclear reactions, mass is converted to energy. Nuclear reactions involve energies a million or more times greater than ordinary chemical reactions. The energy changes are due to the the changes in binding energy as a result of what is called **mass defect**. In order to understand these reactions, it is necessary to clarify these terms.

Mass Defect

The mass of a free proton (1.6725×10^{-24}g) and the mass of a free neutron (1.6748×10^{-24}g) is known. Knowing that the nucleus of elements represents the total number of protons and neutrons, the mass of an element should be easily predicted by adding together the total mass of all neutrons and protons in the nucleus.

In the case of Helium with 2 neutrons and 2 protons in its nucleus, consider the following:

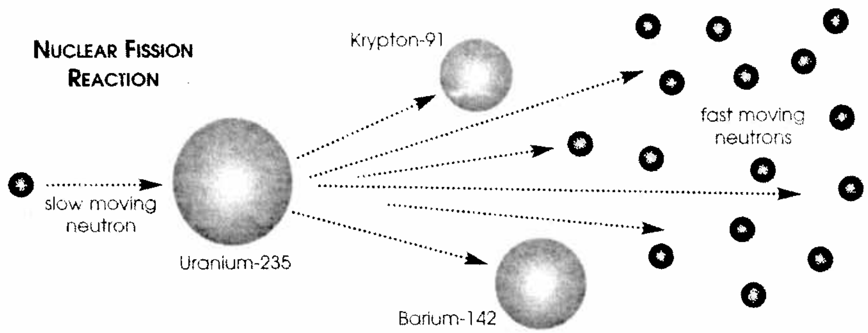
Mass of 2 free neutrons	= 1.6748×10^{-24}g x 2	= 3.3496×10^{-24}g
Mass of 2 free protons	= 1.6725×10^{-24}g x 2	= 3.3450×10^{-24}g
Total Mass of 2 free protons and neutrons		= 6.6946×10^{-24}g

However, the sum of the masses of the nucleons in the Helium nucleus was found to be 6.641236×10^{-24}g. If one total is subtracted from the other, a total mass deficiency of 0.053364×10^{-24}g for every Helium atom is found.

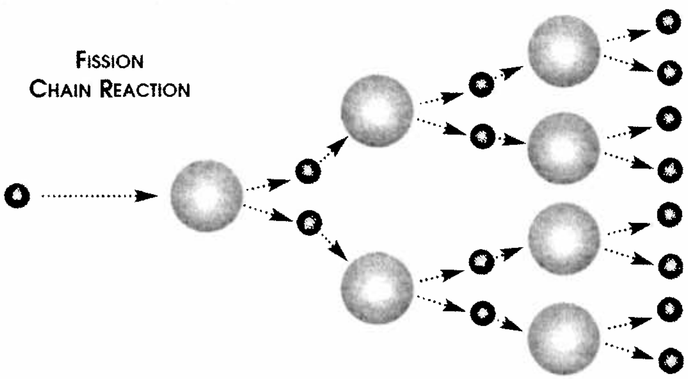
If this value is substituted for the mass factor in Einstein's equation, $E=mc^2$, it can be shown that when nuclear particles merge to make up a nucleus, a great deal of energy is released. This occurs as this small amount of mass is changed into energy. The amount of energy released is called the **binding energy**. It is a measure of the stability of the atom formed. The greater the amount of energy released in the formation of the nucleus, the greater will be the amount of energy required to separate the nucleus into separate particles.

Fission Reaction

A fission reaction results in the "splitting" of heavier nuclei into lighter ones. Fission is brought about by a nucleus capturing slow moving neutrons, which results in the nucleus becoming very unstable. The unstable nucleus splits to form fission fragments of elements of lighter weight, liberation of energy, and release of two or more neutrons. The liberation of energy is the result of conversion of mass into energy.



Only unstable elements of high atomic numbers can be fissioned. When a heavy element fissions, the new elements formed have a more stable configuration because of the greater binding energy per nucleon. In a nuclear reactor, the chain reaction can be controlled with control rods which limit the amount of interacting neutrons. In an atomic bomb, the chain reaction is not controlled.



Real World Connections
Fission Reactors

The energy of fission reactions is related directly with the decrease of mass that occurs. For every gram of uranium-235 that reacts, 80,000 kJ of energy is given off. This amount of energy compares with 30 kilojoule per gram for coal and 2.8 kilojoule per gram for exploding TNT.

However, fission reactions present many complications. First, is the concern with the process itself. During a fission reaction, a slow moving neutron splits a uranium-235 atom into two unequal pieces forming two different elements. In the process, it also produces neutron and beta particles. It is unknown what radioactive elements will be produced because each uranium-235 atom will split in different ways. The result may produce isotopes of rubidium (at number 37) and cesium (at number 55), while another breaks up into isotopes of bromine (at number 35) and lanthanum (at number 57). Yet another may yield isotopes of zinc (at number 530) and samarium (at number 62).

Second, there is concern with the products of the fission reaction. Of the 35 identified elements formed more than 200 isotopes have been identified as products of the fission of uranium-235. These products represent a dangerous hazard, especially strontium-90. In the form of strontium carbonate ($SrCO_3$), it is incorporated in the bones of animals and human beings.

Third, there is concern with the storage of these radioactive products. The amounts produced each month are staggering, and accidents have occurred despite all the precautions taken by the nuclear regulatory agencies. Beyond that, there is danger of fire, earthquakes, and explosion which could cause a "melt-down" with a release of deadly radiation.

Breeder Reactors

The supply of uranium-235 in Earth is finite. An alternative source would be to convert the more abundant isotope, uranium-238 into plutonium-239 (1) which can also undergo fission (2). This is shown in the following summary reaction [bracket denotes intermediate step].

Reaction 1: $^{238}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow \left[{}^{239}_{92}\mathrm{U} \rightarrow {}^{239}_{93}\mathrm{Np} + {}^{0}_{-1}\mathrm{e}\right] \rightarrow {}^{239}_{94}\mathrm{Pu} + 2\,{}^{0}_{-1}\mathrm{e}$

Reaction 2: $^{239}_{94}\mathrm{Pu} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{90}_{38}\mathrm{Sr} + {}^{147}_{56}\mathrm{Ba} + 3\,{}^{1}_{0}\mathrm{n}$

Since the above produces more neutrons than it consumes, a fission reaction can then follow producing additional energy.

Fusion Reaction

When two light nuclei fuse into a heavier nucleus at high temperatures and pressures, an element of more stable configuration (with greater binding energy per nucleon) is formed. The mass of the heavier nucleus formed is less than the sum of the masses of the lighter nuclei. The difference in mass is converted into energy.

Fusion is the process of combining two light nuclei to form a heavier one. The energy released in a fusion reaction is much greater than in a fission reaction. Solar energy is probably the result of the fusion of ordinary hydrogen atoms to form helium. The nuclear reaction of a hydrogen bomb utilizes fission as a trigger for fusion. A typical fusion reaction occurs on the Sun and is represented by the following formula:

$$^{2}_{1}\mathbf{H} + ^{2}_{1}\mathbf{H} \rightarrow ^{4}_{2}\mathbf{He}$$

The energy released by this fusion reaction has been calculated as 57.1 x 10^7 kJ per gram of reactant compared to 8.21 x 10^7 kJ per gram of reactant for a fission reaction. The energy produced in a fusion reaction would be about seven times the energy produced through fission. Nuclear fusion presents the most appealing method of producing great amounts of energy for many reasons.

- **Production** – The production process is safe and does not present a threat. That is, it can be much more easily controlled than other forms of energy producing and shuts down automatically. Also, the isotopes produced are not radioactive but "clean," stable isotopes, that reduce the pollution threat to life.

- **Fuels** – The isotopes of hydrogen, $^{2}_{1}$**H** (**deuterium**) and $^{3}_{1}$**H** (**tritium**), are used as fuels. Heavy water (deuterium oxide) is obtained by concentrating the trace qualities present in water. Tritium is made by a nuclear reaction shown below:

$$^{6}_{3}\mathbf{Li} + ^{1}_{0}\mathbf{n} \rightarrow ^{3}_{1}\mathbf{H} + ^{4}_{2}\mathbf{He}$$

The fuel deuterium is abundant and can be obtained cheaply from sea water. Tritium, another isotope of hydrogen is also used.

There are a number of considerations that must be addressed concerning fusion reactors including:

- There is a high energy requirement – Since each nucleus carries a positive charge, all nuclei repel one another with increasing strength as they are moved closer together. Consequently, for the nuclei to interact, they must have enough kinetic energy to overcome this repulsion.

- The magnitude of repulsion increases with charge. the use of very high temperatures, appears to be very promising for controlled fusion. However, this requires temperatures of several million degrees Celsius.

Technical problems with nuclear fusion, such as the requirement of extremely high temperatures and their containment, continue to challenge nuclear scientists and engineers. Once begun, the containment of the reaction with such high temperatures is extremely difficult.

Uses of Radioisotopes

Radioactive Isotopes have the same physical and chemical properties as nonradioactive isotopes. The only difference is the instability of their nuclei. In physical and chemical reactions, they are both expected to behave the same way. This is the fundamental principle for the use of "tagged" or **tracer** isotopes. Age determination of both living and nonliving specimens, diagnosing, and treating diseases, and analytical biology and chemistry are just a few of the uses for radioactive isotopes.

In transmutation, when a neutron collides with an $^{238}_{92}U$ atom, it causes the atom to change into a new radioactive element as shown below:

$$^{238}_{92}\mathbf{U} + ^{1}_{0}\mathbf{n} \rightarrow ^{239}_{92}\mathbf{U} \rightarrow ^{239}_{93}\mathbf{Np} + ^{0}_{-1}\mathbf{e}$$

Chemical reactivity – Since **radioisotopes** are chemically similar to stable isotopes of the same element, they can be used as tracers to follow the course of a reaction without seriously altering the chemical conditions. Many organic reaction mechanisms are studied by the use of carbon-14 as a tracer.

Based on radioactivity – Radioisotopes are used in medical diagnosis, therapy, food preservation, and as a means of measuring the physical dimensions of many industrial products.

Isotopes with very short half-lives and which will be quickly eliminated from the body are used for diagnostic injections. Technetium-99 is used for pinpointing brain tumors. Iodine-131 is used for diagnosing thyroid disorders. Radium and cobalt-60 are used in cancer therapy. Radiation kills bacteria, yeasts, molds, and insect eggs in foods, permitting the food to be stored for a much longer time.

Based on half-life – Radioisotopes give a fairly consistent method of dating some geologic events. The ratio of uranium-238 to lead-206 in a mineral can be used to determine the age of the mineral. C-14 to C-12 ratio is used in dating living organisms

UNIT X NUCLEAR CHEMISTRY

Key Concepts

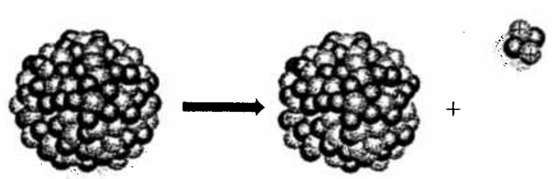
- Stable
- Decay Modes: Alpha, Beta, Positron, Gamma
- Transmutation
- Balancing Nuclear Equations
- Half-Life
- $E=mc^2$
- Uses of radioisotopes
- Risks of radioisotopes
- Fission
- Fusion

I Nuclear Reactions

In the study of nuclear chemistry focus is placed on the nucleus of the atom (nuclide). The nucleus holds protons with a charge of + 1 and neutrons with no charge, each having a mass of 1 amu. The overall charge on the nucleus is positive. Reference Table O. The number of protons (atomic number) identifies the element where as the number of neutrons adds to the mass of the atom. Isotopes are atoms that have the same atomic number (number of protons) but a different number of neutrons. If the ratio of neutrons to protons is proportional the isotope is ***stable***. However if the ratio is not proportional the isotope is unstable (radioactive) and will spontaneously decay by emitting particles or radiation. Every element with anatomic number above 83 is radioactive, some with small atomic numbers may have radioactive isotopes. Reference Table N. Whme a nuclear ***equation is banced*** the total mass and atomic number of the reactants is equal to the products.

$$X + {}^{1}_{0}n \rightarrow {}^{138}_{56}Ba + {}^{95}_{36}Kr$$

The eleme X is represented by ${}^{233}_{92}U$ too keep the equation balanced.



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

II *Radioactive Decay*

The process of decay is called ***transmutation***. This decay can occur naturally or can be induced by bombarding the nucleus with high-energy particles. Each radioactive isotope has its own specific mode and rate of decay. Reference Table N , Reference Table O

a.) ***Alpha decay*** occurs when the radioisotope gives off an alpha particle. An alpha particle is positively charged and has a mass of 4. It is the least penetrating and the least dangerous.

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

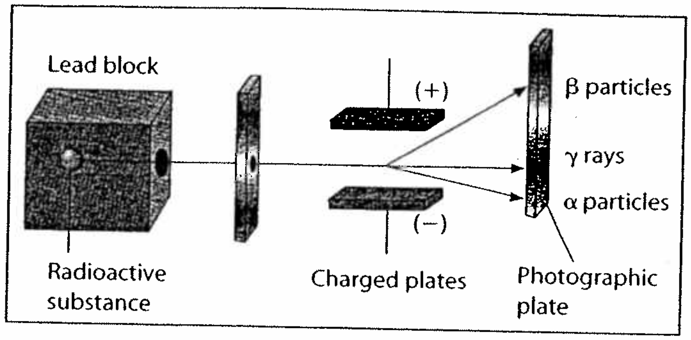
b.) ***Beta decay*** occurs when an isotope emits a beta particle. A beta particle is referred to as a high-speed electron. This means it has a negative charge and no mass. It is the second most penetrating.

Example: $^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e$

c.) ***Positron decay*** occurs when a positron particle is emitted. This particle is described as a positive electron. The mass is zero and the charge is positive. It has moderate penetrating power similar to the beta particle.

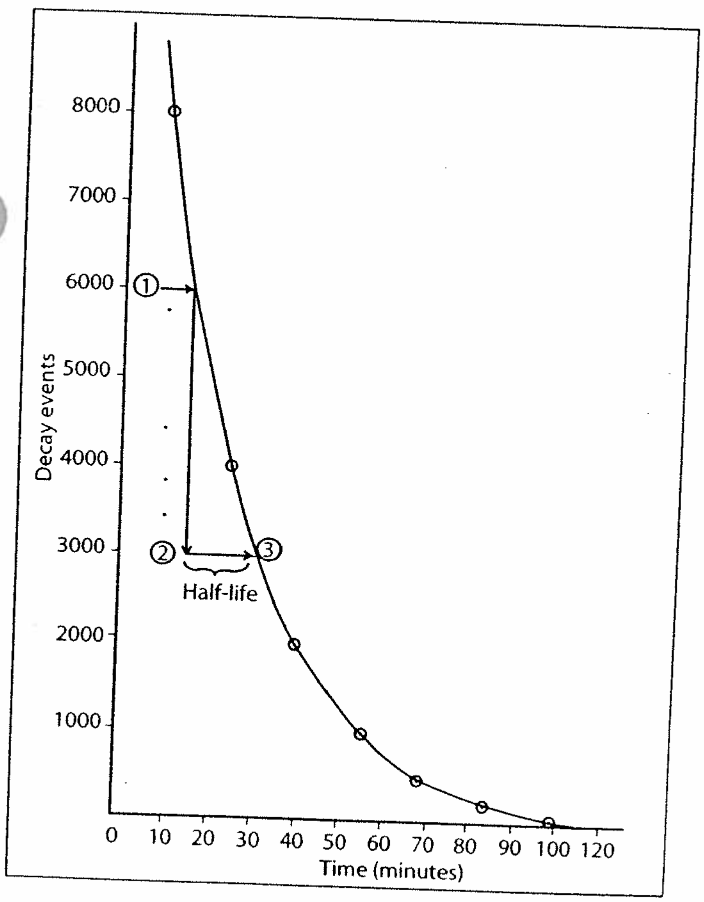
Example: $^{19}_{10}Ne \rightarrow {}^{19}_{9}F + {}^{0}_{+1}e$

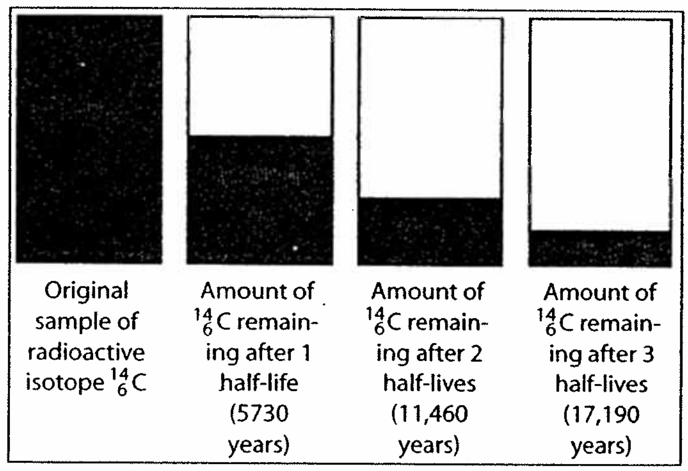
d.) The next type of radiation is not a particle but a high energy ***Gamma*** ray. Gamma rays do not have a mass or charge. They reduce the total amount of energy in the nucleus without affecting the number of protons of the mass. Gamma rays do not show up in transmutation equations.



III Half-Life

The time required for half of a radioactive sample to decay is ***called half-life***. After every unit of time, one half of the substance is decayed. To calculate the number of half-life periods that have occurred use the formula on Reference Table T. The rate of decay of radioactive isotopes (half-life) remains constant: it cannot be altered by changes in pressure, temperature, or chemical combination. It depends on the nature or identity of the radioactive nucleus. Half-lives can range from fractions of seconds to billions of years. (See ref table N)





Example: How much of a radioactive isotope will remain after 16days if its half-life is 4 days?

# of half life periods t/T = 16/4 = 4

fraction remaining = $(1/2)^4 = 1/16$

$1 \rightarrow 1/2 \rightarrow 1/4 \rightarrow 1/8 \rightarrow 1/16$ (each arrow represents a half-life period)

IV Radioactive Isotopes

Radioisotopes have many uses.

a.) Co -60 cancer treatment

b.) I-131 diagnosing and treating thyroid problems

c.) C-14 : C-12 dating living organisms

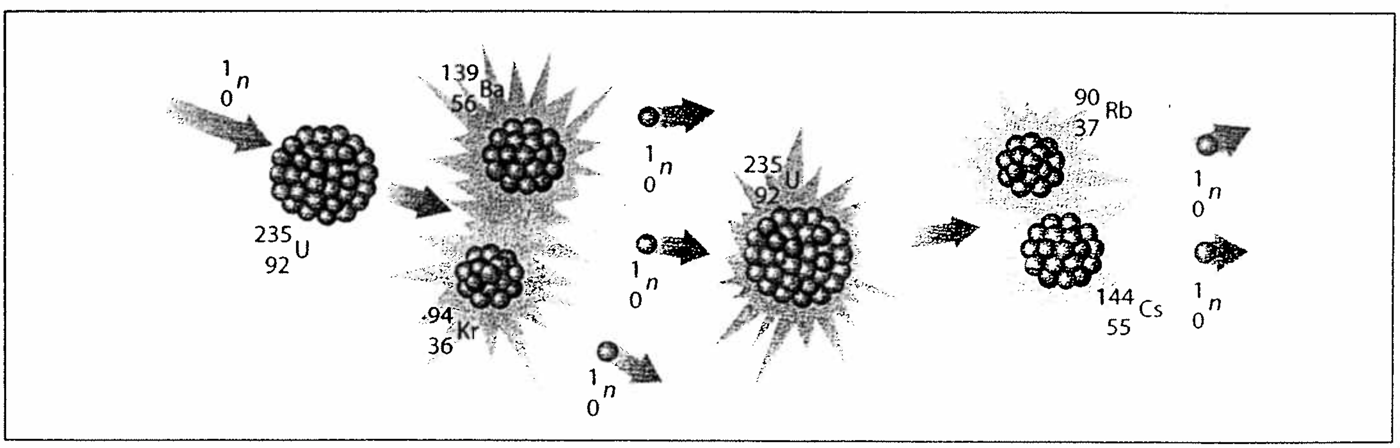
d.) U-238;Pb-206 dating rocks

If a radioisotope very short half-life it can be used in medical applications. The risks inherent in these processes can include biological exposure, long-term storage and disposal, as well as nuclear accidents.

V Fusion versus Fission

Nuclear reactions include natural and artificial transmutation, fission and fusion. Energy released during a nuclear reaction is much greater than the energy released during a chemical reaction. This energy comes from a fractional amount of matter that is converted into energy ($E=mc^2$). The two principal reactions used as sources of energy are nuclear fission and nuclear fusion; both of which have benefits and risks associated with them

a.) ***Fission*** occurs when neutrons bombard radioactive atoms. This causes the atom to split into halves and an enormous amount of energy is released. The obvious benefit is the amount of energy obtained but the problems include thermal pollution due to the large amount of heat also generated, and radioactive waste disposal. Because of the length of half-lives many waste products are dangerous for centuries. Also once started the process continues in a chain reaction that can get out of control.



b.) ***Fusion*** occurs when light nuclei are joined to form heavier and more stable ones. This is the process used by stars to produce energy. For fusion to occur very high temperatures are needed to overcome the natural repulsion the two positively charged nuclei feel.