

SCH 2203 NUCLEAR CHEMISTRY AND RADIOCHEMISTRY (45 hours)

Course Description

A brief introduction into radioactivity and nuclear reactions, half-life, factors determining stability of nuclei; different kinds of ionising radiations and their properties, modes of radioactive decay, interaction of radiation with matter; effects of high energy radiations, applications of radio isotopes and radiation Chemistry in areas such as industry, biology, medicine, agriculture and nuclear reactors. Handling nuclear waste, nuclear accidents.

Teaching Methodology:

Lectures and tutorials

Course assessment

Written CATS 30%, final written examination 70%

Course Journals

1. Journal of nuclear material, Elsevier science. ISSN: 1071-3581
2. Journal of nuclear science and technology. Taylor and Francis Ltd. ISSN: 0022-3131

Course Journals

1. Atomic data and nuclear data tables, Academic press inc., Elsevier science. ISSN: 0092-640X

Course textbooks

1. Modern nuclear chemistry, Walter D. Loveland, David J. Morrissey and Glenn T. Seaborg, Wiley- interscience, 1st edition (2001), ISBN-10: 0471115320, ISBN-13: 978-0471115328
2. Radiochemistry and nuclear chemistry, Gregory Choppin, Jan Rydberg and Jan-dov Liljenzin, Butterworth-Heinemann, 3rd edition (2001). ISBN-10: 0750674636, ISBN-13: 0750674638

Reference textbooks

1. Radiation, detection and measurement, Glenn F. Knoll, Wiley, 4th edition (2010).
ISBN-10: 0470131489, ISBN-13: 978-0470131480
2. Introduction to Nuclear Science Jeff C. Bryan, (2008) CRC Press; 1 edition ISBN-13:
978-1420061642

Introduction

The atomic theory

In 1911, Ernest Rutherford published his atomic theory and he based his theory on a model of the atom known as the *nuclear atom* and having these features

1. Most of the mass and all of the positive charge of an atom are centered in a very small region called the *nucleus*. The remainder of the atom is mostly *empty space*.
2. The magnitude of the positive charge is different for different atoms and is approximately one-half the atomic weight of the element.
3. There are as many electrons outside the nucleus as there are units of positive charge on the nucleus. The atom as a whole is electrically neutral.

Rutherford's nuclear atom suggested the existence of **positively charged** fundamental particles of matter in the nuclei of atoms. Rutherford himself discovered these particles, **called protons**, in 1919 in studies involving the scattering of particles by nitrogen atoms in air. The protons were freed as a result of collisions between particles and the nuclei of nitrogen atoms. At about this same time, **Rutherford predicted** the existence in the nucleus of electrically neutral fundamental particles. In 1932, James Chadwick showed that a newly discovered penetrating radiation consisted of beams of *neutral* particles. These particles, **called neutrons**, originated from the nuclei of atoms.

Properties of the Three Fundamental Particles

	Proton	Electron	Neutron
Charge / C	$+1.602 \times 10^{-19}$	-1.602×10^{-19}	0
Charge number (relative charge)	1	-1	0
Rest mass / kg	1.673×10^{-27}	9.109×10^{-31}	1.675×10^{-27}
Relative mass	1837	1	1839

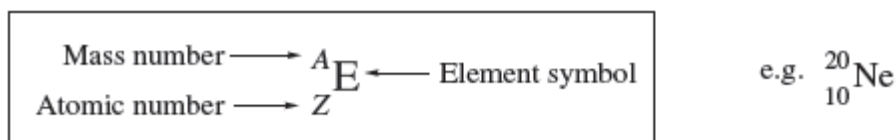
A neutron and a proton have approximately the same mass and, relative to these, an electron has negligible mass

The nucleus of an atom consists of protons and neutrons and is positively charged. The electrons occupy a region of space around the nucleus. Nearly all the mass of an atom is concentrated in the nucleus

Atomic number, mass number and isotopes

A nuclide is any atomic species of which the proton/atomic number, Z , and nucleon/mass number, A , are specified. Nucleon refer to the total number of protons and neutrons

A shorthand method of showing the atomic number and mass number of a nuclide along with its symbol, E , is:



Atomic number = Z = number of protons in the nucleus =
number of electrons

Mass number = A = number of protons + number of
neutrons

Number of neutrons = $A - Z$

Relative atomic mass

Since the electrons are of minute mass, the **mass of an atom** essentially depends upon the number of protons and neutrons in the nucleus. The mass of a single atom is a very small, non-integral number, and for convenience we adopt a system of relative atomic masses.

We define the atomic mass unit as 1/12th of the mass of a ${}^{12}_6\text{C}$ atom so that it has the value 1.660×10^{-27} kg. Relative atomic masses (A_r) are thus all stated relative to ${}^{12}_6\text{C} = 12.0000$.
The masses of the proton and neutron can be considered to be ≈ 1 u where u is the atomic mass unit

($1 \text{ u} \approx 1.660 \times 10^{-27} \text{ kg}$).

Atoms that have the *same* atomic number (Z) but *different* mass numbers (A) are called **isotopes**.

Electromagnetic Radiation and Introduction to Ionizing Radiations

Radiation can be defined as the propagation of energy through matter or space. It can be in the form of electromagnetic waves or energetic particles.

Electromagnetic radiation is most simply defined as light, not all light is visible to the human eye. Electromagnetic radiation is broken up into regions based on the frequency of the light, the full range of radiation is called the electromagnetic spectrum

The major regions are radio, micro, infrared, visible, ultra violet, x-rays and gamma rays.

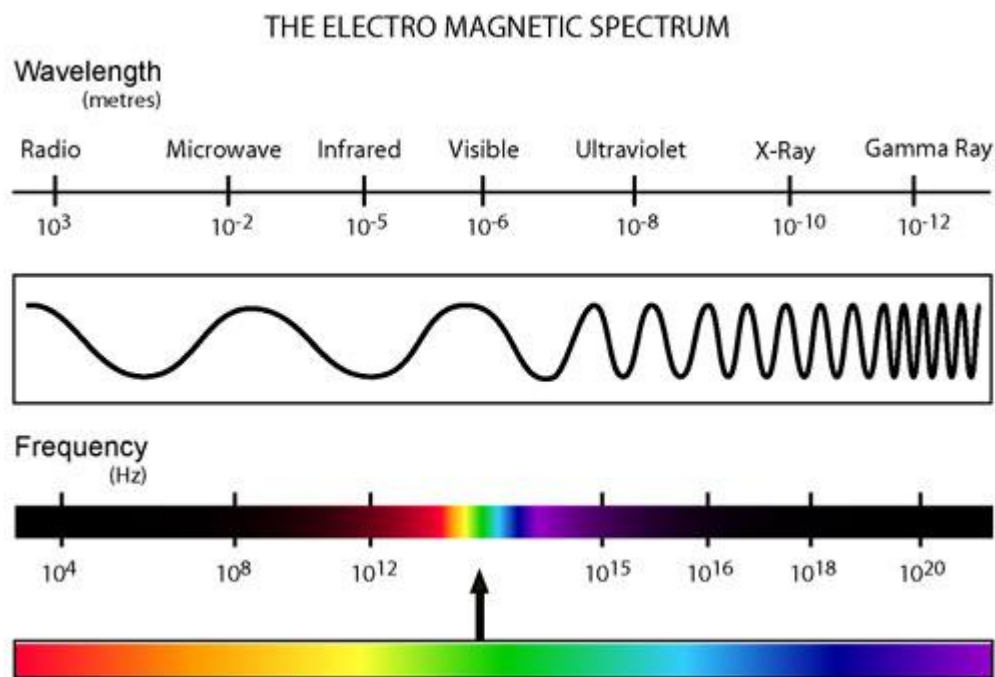


Figure 1: Electromagnetic spectrum

Ionizing radiation has the ability to knock an electron from an atom, i.e. to ionize. Examples of ionizing radiation include:

- i. alpha particles
- ii. beta particles
- iii. neutrons
- iv. gamma rays
- v. x-rays

Non-ionizing radiation does not have enough energy to ionize atoms in the material it interacts with. Examples of non-ionizing radiation include:

- i. microwaves
- ii. visible light

- iii. radio waves
- iv. TV waves
- v. Ultraviolet radiation (except for the very shortest wavelengths)

RADIOACTIVITY

Radioactivity is the spontaneous emission of particles and/or electromagnetic radiation by unstable nuclei, also known as radionuclides.

Radioactivity was discovered in 1896 by the French scientist Henri Becquerel, while working on phosphorescent materials. These materials glow in the dark after exposure to light, and he suspected that the glow produced in cathode ray tubes by X-rays might be associated with phosphorescence. He wrapped a photographic plate in black paper and placed various phosphorescent salts on it. All results were negative until he used uranium salts. The result with these compounds was a blackening of the plate. These radiations were called Becquerel Rays. Soon after Becquerel's discovery, Marie Sklodowska Curie began studying radioactivity and completed much of the pioneering work on nuclear changes. Curie found that radiation was proportional to the amount of radioactive element present, and she proposed that radiation was a property of atoms (as opposed to a chemical property of a compound). Marie Curie was the first woman to win a Nobel Prize and the first person to win two (the first, shared with her husband Pierre and Becquerel for discovering radioactivity; the second for discovering the radioactive elements radium and polonium).

Differences between Chemical and Nuclear Reactions:

Chemical and nuclear reactions are very different:

Chemical Reactions	Nuclear Reactions
Usually only valence electrons are exchanged but nuclei are unchanged.	Nuclei undergo changes while orbital electrons are usually not involved.
Elements remain unchanged as new compounds form.	Entirely different elements form.
Relatively small energy changes occur.	Energy changes are millions of times greater.
Reaction rate is affected by conc., temp., pressure and catalysts.	Reaction rate is unaffected by external factors.

Nuclear reactions involve changes in particles in an atom's nucleus and thus cause a change in the atom itself. All elements heavier than bismuth (Bi) (and some lighter) exhibit natural radioactivity and thus can "decay" into lighter elements. Unlike normal chemical reactions that form molecules, nuclear reactions result in the transmutation of one element into a different isotope or a different element altogether (remember that the number of protons in an atom defines the element, so a change in protons results in a change in the atom).

Nuclear Stability

A key factor that determines the stability of a nuclide is the ratio of the number of neutrons to the number of protons, the N/Z ratio. For lighter nuclides, one neutron for each proton is enough to provide stability ($N/Z = 1$).

For heavier nuclides, in which the number of protons and their corresponding repulsions increases, the number of neutrons increases even more to stabilize them. If the N/Z ratio is either too high or not high enough, the nuclide is unstable and decays.

There is a narrow band of stability that gradually increases from an N/Z ratio of 1 near $Z=10$ for ^{20}Ne to an N/Z ratio slightly greater than 1.5 near $Z=83$ for ^{209}Bi .

Several key points are seen:

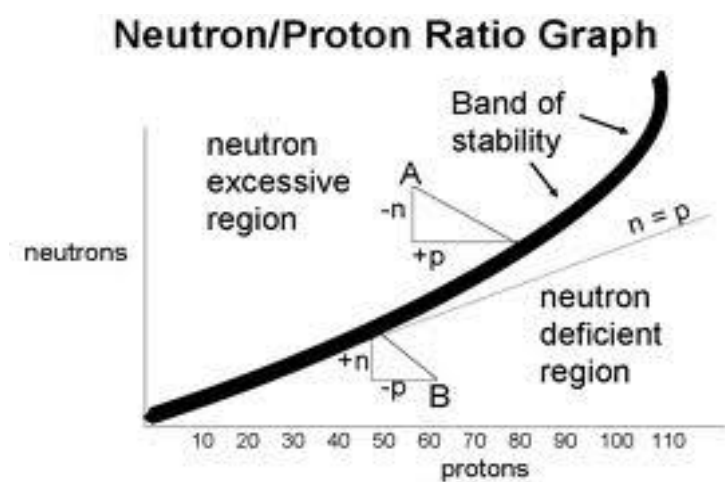
1. Very few stable nuclides exist with $N/Z < 1$; the only two are ^1_1H and ^3_2He . For the lighter stable nuclides, $N/Z \sim 1$, i.e., ^4_2He , $^{12}_6\text{C}$, $^{16}_8\text{O}$ and $^{20}_{10}\text{Ne}$ are particularly stable.
2. The N/Z ratio of stable nuclides gradually increases as Z increases. No stable nuclide exists with $N/Z = 1$ for $Z > 20$. Thus for $^{56}_{26}\text{Fe}$, $N/Z = 1.15$, for $^{107}_{47}\text{Ag}$, $N/Z = 1.28$ and for $^{184}_{74}\text{W}$, $N/Z = 1.49$.
3. All nuclides with $Z > 83$ (Bi) are unstable. Bismuth-209 is the heaviest stable nuclide. Therefore, the largest members of Group 1A (Fr), 2A (Ra), 6A (Po), 7A (At) and 8A (Rn) are radioactive as well as the actinides and known elements of the fourth transition series [Period 7, Actinium (89) to Ununbium (112)].

Nuclear scientists explain these data in terms of two opposing forces. Electrostatic repulsive forces between protons would break the nucleus apart if not for the presence of an attractive force that exists between all nucleons (neutrons and protons) called the '*strong force*'. It is about 100 times stronger than the repulsive force but operates only over short distances within

the nucleus. Competition between the attractive strong force and the repulsive electrostatic force determines nuclear stability.

Nuclear stability follows some general trends – stable isotopes with an even number of protons and an even number of neutrons are the most abundant (168). Isotopes with an even number of protons and an odd number of neutrons (57), or vice versa (50), are relatively stable. Stable isotopes with an odd number of protons and an odd number of neutrons are fairly rare. One model of nuclear structure postulates that protons and neutrons lie in *nucleon shells*, or energy levels, and that stability results from the *pairing* of like nucleons. This leads to stability of even values of N and Z (like the stability of electron pairing)

Nuclei that contain a *magic number* (2, 8, 20, 50, 82, or 126) protons or neutrons are very stable. These magic numbers are thought to correspond to the numbers of protons or neutrons in filled *nucleon shells*.



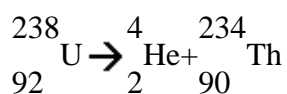
1. If one plots the number of neutrons in the nucleus of a particular radionuclide vs the number of protons for the same nuclide for all three thousand known nuclides, the graph above will be obtained. The band represents the “band of stability” and its edges are not as smooth as in the diagram. Any nuclide falling in the band of stability will be stable and therefore not radioactive.
2. Only about 8% of all known nuclides are stable; the remainder plot in a region above the curve known as the “neutron excessive region” or a region below the curve known as the “neutron deficient region”.
3. If a nuclide plots in the “neutron excessive region” represented by point A in the diagram, the implication is that it has too many neutrons per proton and, as reflected in the diagram, must lose a neutron and gain a proton to decrease the ratio and achieve stability. On the other

hand, if a nuclide plots in the “neutron deficient region” represented by point B in the diagram, the implication is that it has too few neutrons per proton and, as reflected in the diagram, must lose a proton and gain a neutron to increase the ratio and achieve stability.

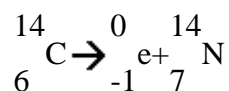
4. As indicated in the diagram, the curve is not linear but gently curves upward as a function of increased proton number, meaning that to achieve stability, the number of neutrons must increase at a somewhat greater rate than the number of protons. For example, for a Z number of 80, it might require 120 neutrons and 80 protons to achieve stability whereas for a Z number of 10, it would take 10 neutrons and 10 protons to achieve stability. These would represent n/p ratios of 1.5:1.0 and 1.0:1.0, respectively. In reality, the relationship is linear only through Z = 8, after which there are deviations. For example, F-18 has 9 neutrons and 9 protons, with a n/p ratio of 1.0:1.0, but it is radioactive.

Types of Radioactivity

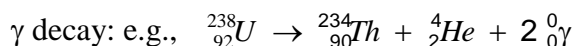
1. **Alpha Radiation (α)** is the emission of an alpha particle from an atom's nucleus. An α particle contains two protons and two neutrons (and is similar to a He nucleus: ${}^4_2\text{He}$). When an atom emits an α particle, the atom's atomic mass will decrease by four units (because two protons and two neutrons are lost) and the atomic number (z) will decrease by two units. The element is said to "transmute" into another element that is two z units smaller. An example of an α transmutation takes place when uranium decays into the element thorium (Th) by emitting an alpha particle, as depicted in the following equation:



2. **Beta Radiation (β)** is the transmutation of a neutron into a proton and an electron (followed by the emission of the electron from the atom's nucleus: ${}^0_{-1}\text{e}$). When an atom emits a β particle, the atom's mass will not change (since there is no change in the total number of nuclear particles), however the atomic number will increase by one (because the neutron transmuted into an additional proton). An example of this is the decay of the isotope of carbon named carbon-14 into the element nitrogen:

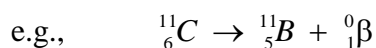


3. **Gamma Radiation (γ)** involves the emission of electromagnetic energy (similar to light energy) from an atom's nucleus. No particles are emitted during gamma radiation, and thus gamma radiation does not itself cause the transmutation of atoms, however γ radiation is often emitted during, and simultaneous to, α or β radioactive decay. X-rays, emitted during the beta decay of cobalt-60, are a common example of gamma radiation.



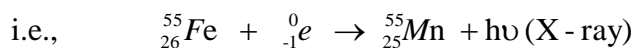
Recall that when an atom is in an excited electronic state, it reduces its energy by emitting photons, usually in the UV or visible ranges. Similarly, a nucleus in an excited state lowers its energy by emitting γ photons (shorter λ , higher energy than UV). Many nuclear changes leave the nucleus in an excited state, so γ emission accompanies most other types of decay.

4. **Positrons (β^+)**: Positrons or positive electrons are emitted when a proton converts to a neutron, i.e., ${}^1_1\text{p} \rightarrow {}^1_0\text{n} + {}^0_{+1}\beta$. β^+ decay is the opposite of β decay (in which a neutron converts to a proton) and results in a *daughter* nuclide with the same A but one less proton (Z) than the *parent*. Positrons have low to moderate penetrating power and, like alpha particles, are attracted toward the negative electric field of a cathode and deflected by magnetic fields. β^+ decay occurs only in some lighter synthetic isotopes that are short on neutrons.



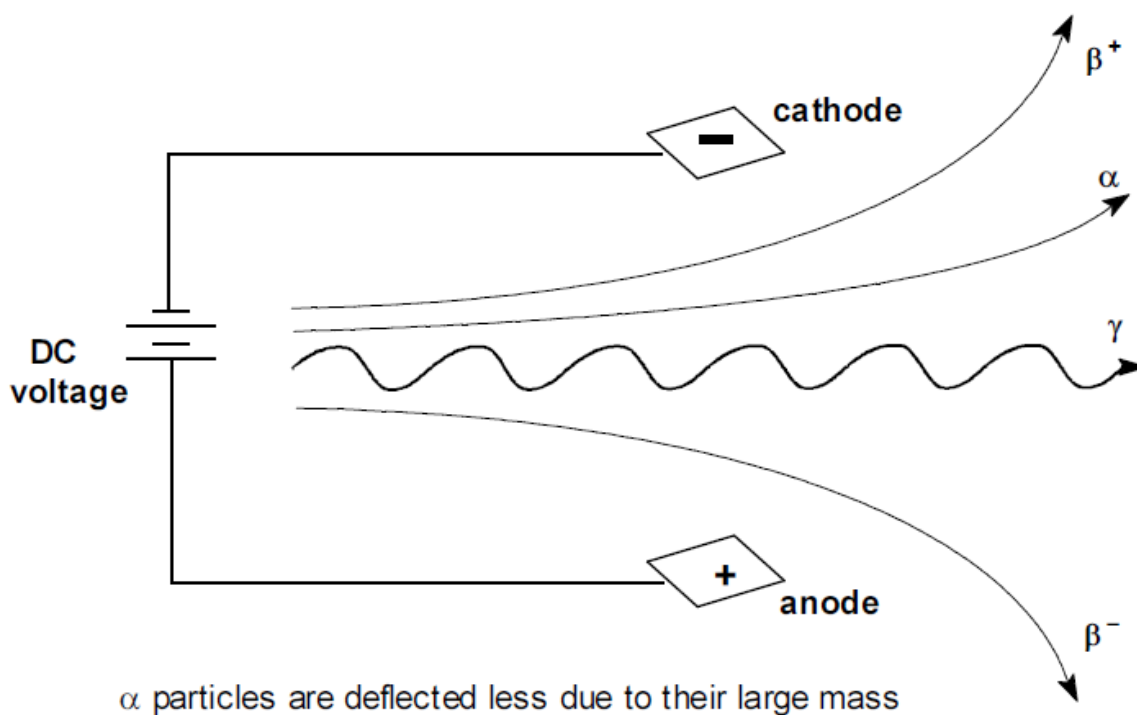
5. **Electron Capture**: occurs when the nucleus of an atom draws in a surrounding electron, usually one from the lowest energy level. The result is that a nuclear proton is transformed into a neutron, i.e., ${}^1_1\text{p} + {}^0_{-1}\text{e} \rightarrow {}^1_0\text{n}$

The orbital vacancy is quickly filled by an electron moving down from a higher energy level with the corresponding release of an X-ray photon. Radioactive Fe forms stable Mn by electron capture:



Electron capture has the same effect as positron decay: Z lowers by 1, A is unchanged, even though the process is entirely different.

EFFECT OF ELECTRIC FIELD ON RADIOACTIVE EMISSIONS



Assignment

- 1) Write balanced equations for the following nuclear reactions:
 - i. Naturally occurring thorium-232 undergoes α decay.
 - ii. Chlorine-36 undergoes electron capture.
 - iii. A nuclide undergoes β decay and produces cesium-133.
- 2) Describe the nuclear model of the atom, including the general location of the protons, neutrons, and electrons, the relative size of the nucleus compared to the size of the atom, and the modern description of the electron.
- 3) Explain why gamma rays often accompany alpha emission, beta emission, positron emission, and electron capture.
- 4) Oxygen-13 atoms undergo positron emission, so they can be used to generate PET (positron emission tomography) scans. Write the nuclear equation for this reaction.
- 5) Complete the following nuclear equations and identify X in each case: (4 marks)
 - i. ${}^{26}_{12}\text{Mg} + {}^1_1\text{P} \rightarrow {}^4_2\alpha + \text{X}$
 - ii. ${}^{235}_{92}\text{U} + {}^1_0\text{n} \rightarrow {}^{94}_{36}\text{Kr} + {}^{139}_{56}\text{Ba} + 3\text{X}$
 - iii. ${}^{20}_8\text{O} \rightarrow {}^{20}_9\text{F} + \text{X}$
 - iv. ${}^{32}_{16}\text{S} + {}^1_0\text{n} \longrightarrow {}^1_1\text{p} + \text{x}$

NUCLEAR KINETICS

Radionuclides have different stabilities and decay at different rates. Some decay nearly completely in a fraction of a second and others only after millions of years. The rates of all radioactive decays are independent of temperature and pressure and obey *first-order kinetics*.

The *decay rate* of a radioactive sample is the change in the number of nuclides (N) per unit time or number of disintegrations per second.

The basic unit of radioactivity is the **curie (Ci)**: one curie equals the number of nuclei disintegrating each second in 1 gram of radium-226:

$$1 \text{ Ci} = 3.70 \times 10^{10} \text{ disintegrations per second (dps)}$$

Each radioactive element has a unique decay rate dependent only upon the amount present at any time.

Following the first-order rate law, *decay rate*, r , can be expressed as:

$$r = \lambda N$$

This rate law can also be written as

$$r = - \frac{dN}{dt} = \lambda N$$

Where N is the quantity of the radioactive material at time ' t ', λ is a rate constant unique to each radioactive substance and ' t ' is the time.

This equation is a differential equation that relates the rate of change in a concentration to the concentration itself. Integration of this equation produces the corresponding **integrated rate law**, which relates the concentration to time.

$$-\frac{\Delta N}{\Delta t} = \lambda N \rightarrow -\frac{dN}{dt} = \lambda N \rightarrow -\frac{dN}{N} = \lambda dt \rightarrow \int \left(-\frac{dN}{N} = \lambda dt \right) \rightarrow -\ln N = \lambda t + C$$

solving for C at $t = 0$ gives $C = -\ln N_0$.

$$\text{substituting for } C \text{ gives: } -\ln N = \lambda t - \ln N_0 \rightarrow (\ln N_0 - \ln N) = \lambda t \rightarrow \ln \frac{N_0}{N} = \lambda t \quad \text{or} \quad \log \frac{N_0}{N} = \frac{\lambda t}{2.303}$$
$$\text{or } N = N_0 e^{-\lambda t}$$

Remember:

Recall from calculus that (or check a table of integrals): $\int 1/x \, dx = \ln x$ and $\int dx = x$ (*definite integrals*)

$$\int x^n dx = \frac{1}{n+1} x^{n+1} + c$$

Example:

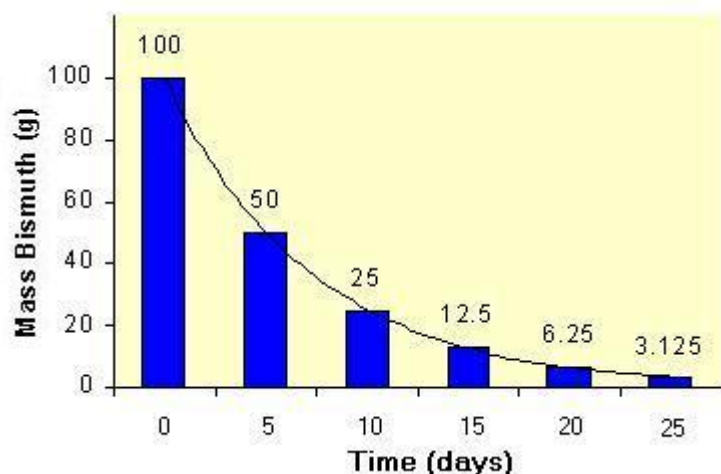
$$\int x^5 dx = \frac{1}{6} x^6 + c$$

Natural logarithms use the number ($e = 2.7183\dots$) as their base instead of the number 10

To convert a natural logarithm to base-10 logarithm, divide by the conversion factor 2.303.

Half-life

Radioactive decay proceeds according to a principal called the half-life. The half-life ($T_{1/2}$) is the amount of time necessary for one-half of the radioactive material to decay. For example, the radioactive element bismuth (^{210}Bi) can undergo alpha decay to form the element thallium (^{206}Tl) with a reaction half-life equal to five days. If we begin an experiment starting with 100 g of bismuth in a sealed lead container, after five days we will have 50 g of bismuth and 50 g of thallium in the jar. After another five days (ten from the starting point), one-half of the remaining bismuth will decay and we will be left with 25 g of bismuth and 75 g of thallium in the jar. As illustrated, the reaction proceeds in halves, with half of whatever is left of the radioactive element decaying every half-life period.



The half-life, usually symbolized by $t_{1/2}$, is the time required for N to drop from its initial value N_0 to $N_0/2$.

Using the integrated form of the first order rate law we find that

$$\ln(1/2) = -\lambda t_{1/2}$$

Assignment

- 1) How much time is required for a 10 mg sample of ^{51}Cr to decay to 3 mg if it has a half-life of 27.8 days
- 2) The half-life of Tritium is 12.3 years. If 48.0 mg of tritium is released from a nuclear power plant, what mass of this nuclide will remain after 49.2 years?
- 3) Strontium-90 has a $t_{1/2}$ of 29 yr. If a sample has an activity of 1.2×10^{12} dps currently, find the activity and fraction of nuclei that have decayed after 60 years.
- 4) Na-24 with a half-life of 15h is used to study blood circulation. If a patient is injected with a $^{24}\text{NaCl}$ solution whose activity is 2.5×10^9 dps, how much of the activity is present in the patient's body and excreted as fluid after 4 days?

NATURAL RADIOACTIVITY

Nuclear reactions which occur spontaneously are said to be an example of natural radioactivity. There are three naturally occurring radioactive series among the elements in the periodic table. These are known as the uranium series, the actinium series and the thorium series, each named after the element at which the series start (except the actinium series which starts with a different uranium isotope). Each series decays through a number of unstable nuclei by means of alpha and beta emission, until each series end on a different stable isotope of lead

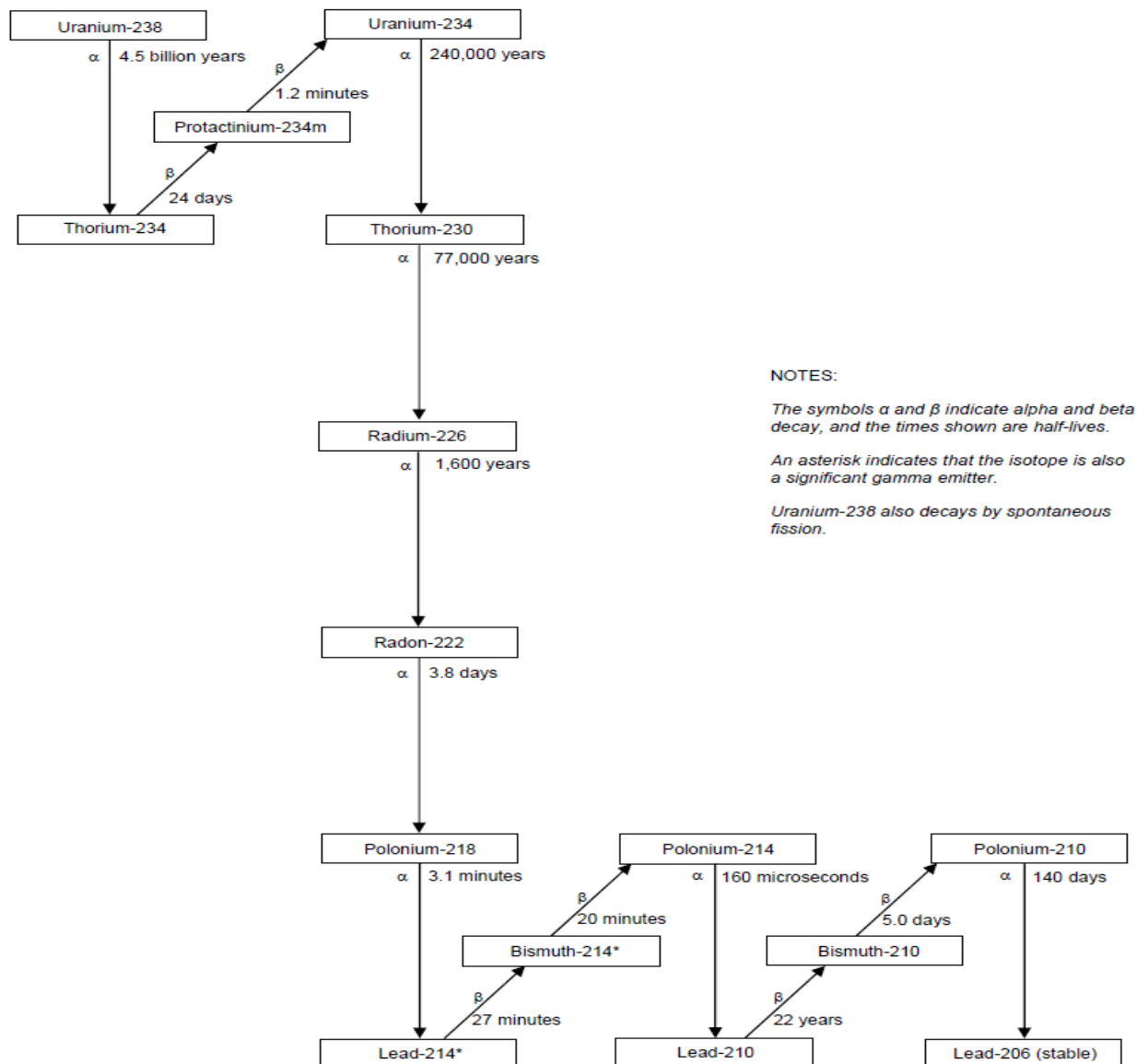


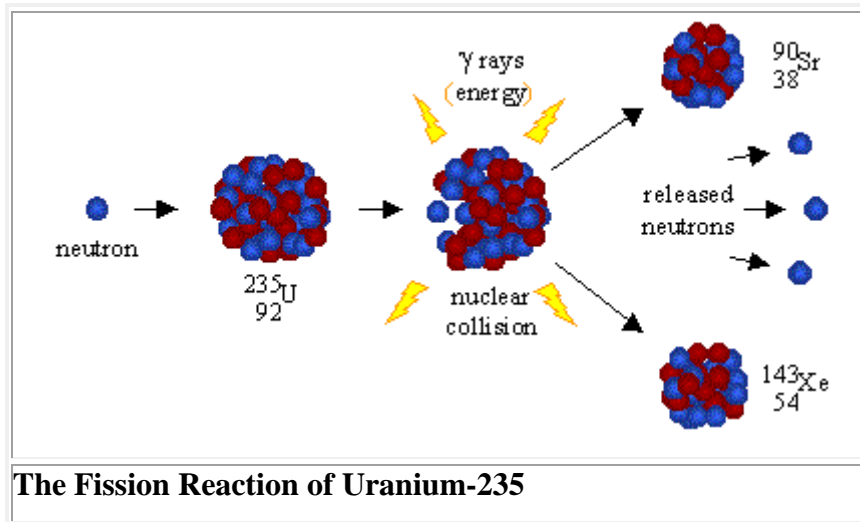
FIGURE N.1 Natural Decay Series: Uranium-238

ARTIFICIAL RADIOACTIVITY

Not all nuclear reactions are spontaneous. These reactions occur when stable isotopes are bombarded with particles such as neutrons. This method of inducing a nuclear reaction to proceed is termed artificial radioactivity. This meant new nuclear reactions, which wouldn't have been viewed spontaneously, could now be observed.

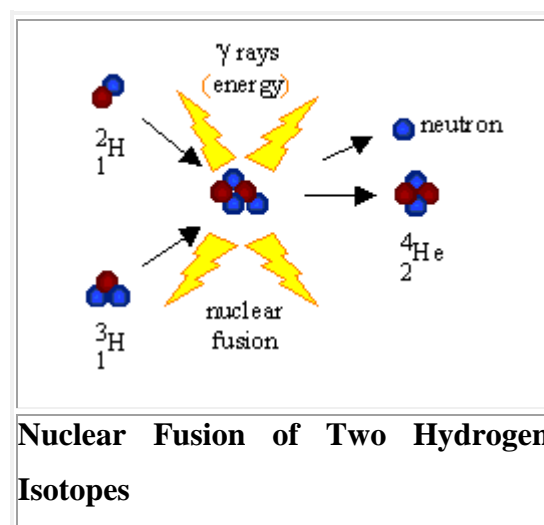
While many elements undergo radioactive decay naturally, nuclear reactions can also be stimulated artificially. Although these reactions also occur naturally, we are most familiar with them as stimulated reactions. There are two such types of nuclear reactions:

1. Nuclear fission: reactions in which an atom's nucleus splits into smaller parts, releasing a large amount of energy in the process. Most commonly this is done by "firing" a neutron at the nucleus of an atom. The energy of the neutron "bullet" causes the target element to split into two (or more) elements that are lighter than the parent atom.



During the fission of U235, three neutrons are released in addition to the two daughter atoms. If these released neutrons collide with nearby U235 nuclei, they can stimulate the fission of these atoms and start a self-sustaining nuclear chain reaction. This chain reaction is the basis of nuclear power. As uranium atoms continue to split, a significant amount of energy is released from the reaction. The heat released during this reaction is harvested and used to generate electrical energy.

Nuclear fusion: reactions in which two or more elements "fuse" together to form one larger element, releasing energy in the process. A good example is the fusion of two "heavy" isotopes of hydrogen (deuterium: H2 and tritium: H3) into the element helium.



Fusion reactions release tremendous amounts of energy and are commonly referred to as thermonuclear reactions. Although many people think of the sun as a large fireball, the sun (and all stars) are actually enormous fusion reactors. Stars are primarily gigantic balls of hydrogen gas under tremendous pressure due to gravitational forces. Hydrogen molecules are fused into helium and heavier elements inside of stars, releasing energy that we receive as light and heat. Because of the high temperatures involved in a fusion reaction, no currently known material can confine these reactions. At such high temperatures, all molecules dissociate and atoms ionize, resulting in the formation of a *fourth state of matter*, called a plasma, a neutral gaseous mixture of positive nuclei and electrons.

Nuclear transmutation

Only about 300 of the more than 3600 known isotopes occur naturally. The remainder have been made by **nuclear transmutation**. **Nuclear transmutation** is the conversion of one chemical element or isotope into another. In other words, atoms of one element can be changed into atoms of other element by 'transmutation'. This occurs either through nuclear reactions (in which an outside particle reacts with a nucleus), or through radioactive decay (where no outside particle is needed).

Such transmutation is often brought about by bombardment of an atom with a high-energy particle such as a proton, neutron, or α particle. In the ensuing collision between particle and atom, an unstable nucleus is momentarily created, a nuclear change occurs, and a different element is produced. The first nuclear transmutation was accomplished in 1917 by Ernest Rutherford, who bombarded ^{14}N nuclei with α particles and found that ^{16}O was produced.



The cobalt-60 used in radiation therapy for cancer patients can be prepared by neutron bombardment of iron-58. Iron-58 first absorbs a neutron to yield iron-59, the iron-59 undergoes β decay to yield cobalt-59, and the cobalt-59 then absorbs a second neutron to yield cobalt-60



The Mass Defect and Nuclear Binding Energy

Nuclear binding is the energy required to split a nucleus of an atom into its component parts. The component parts are neutrons and protons, which are collectively called nucleons. The binding energy of nuclei is always a positive number, since all nuclei require net energy to separate them into individual protons and neutrons. Thus, the actual mass of an atom is always less than the sum of the individual masses of the constituent protons and neutrons when separated because energy is removed when the nucleus is formed. This notable difference is a measure of the nuclear binding, which is a result of forces that hold the nucleus together. Because these forces result in the removal of energy when the nucleus is formed, and this energy has mass, mass is removed from the total mass of the original particles, and the mass is missing in the resulting nucleus. This missing mass is known as the mass defect, and represents the energy released when the nucleus is formed. Nuclear binding energy is the energy required to split a nucleus of an atom into its component parts. The component parts are neutrons and protons, which are collectively called nucleons. The binding energy of nuclei is always a positive number, since all nuclei require net energy to separate them into individual protons and neutrons. Thus, the mass of an atom's nucleus is always less than the sum of the individual masses of the constituent protons and neutrons when separated. This notable difference is a measure of the nuclear binding energy, which is a result of forces that hold the nucleus together. Because these forces result in the removal of energy when the nucleus is formed, and this energy has mass, mass is removed from the total mass of the original particles, and the mass is missing in the resulting nucleus. This missing mass is known as the mass defect, and represents the energy released when the nucleus is formed.

According to Einstein's theory of relativity, mass and energy are related by $E = mc^2$. The traditional conservation of mass and conservation of energy laws have been combined to state that *the total quantity of mass-energy in the universe is constant*. According to this law, when any reaction that produces or consumes energy occurs, there must be a corresponding loss or gain in mass.

Nuclear binding energies are usually expressed in terms of kJ/mole of nuclei or MeV's/nucleon. Calculation of the nuclear binding energy involves the following three steps:

- i. **Determining the Mass Defect**
- ii. **Conversion of Mass Defect into Energy**
- iii. **Expressing Nuclear Binding Energy as Energy per Mole of Atoms, or as Energy per Nucleon**

A neutron has a slightly larger mass than the proton. These are often given in terms of an atomic mass unit, where one atomic mass unit (amu) is defined as 1/12th the mass of a carbon-12 atom

Particle	Mass (kg)	Mass (amu)
1 atomic mass unit	1.660540×10^{-27} kg	1.000 amu
neutron	1.674929×10^{-27} kg	1.008664 amu
proton	1.672623×10^{-27} kg	1.007276 amu
electron	9.109390×10^{-31} kg	0.00054858 amu

The carbon-12 atom has a mass of 12.000 amu, and yet it contains 12 objects (6 protons and 6 neutrons) that each have a mass greater than 1.000 amu, not to mention a small contribution from the 6 electrons.

This is true for all nuclei, that the mass of the nucleus is a little less than the mass of the individual neutrons, protons, and electrons. This missing mass is known as the mass defect, and represents the binding energy of the nucleus.

The binding energy is the energy you would need to put in to split the nucleus into individual protons and neutrons. To find the binding energy, add the masses of the individual protons, neutrons, and electrons, subtract the mass of the atom, and convert that mass difference to energy. For carbon-12 this gives:

$$\text{Mass defect} = \Delta m = 6 * 1.008664 \text{ amu} + 6 * 1.007276 \text{ amu} + 6 * 0.00054858 \text{ amu} - 12.000 \text{ amu} = 0.098931 \text{ amu}$$

Conversion of Mass Defect into Energy

To convert the mass defect into energy:

- Convert the mass defect into kilograms ($1 \text{ amu} = 1.6606 \times 10^{-27} \text{ kg}$)
- Convert the mass defect into its energy equivalent using Einstein's equation $\Delta E = \Delta mc^2$, where $c = 2.9979 \times 10^8 \text{ m/s}$.

Expressing Nuclear Binding Energy as Energy per Mole of Atoms, or as Energy per Nucleon

- To convert the energy to kJ/mol of nuclei** we will simply employ the conversion factors for converting joules into kilojoules ($1 \text{ kJ} = 1000 \text{ J}$) and for converting individual particles into moles of particles (Avogadro's Number).
- To convert the binding energy to MeV (megaelectron volts) per nucleon** we will employ the conversion factor for converting joules into MeV ($1 \text{ MeV} = 1.602 \times 10^{-13} \text{ J}$) and the number of nucleons (protons and neutrons) which make up the nucleus.

$$1 \text{ MeV} = 10^6 \text{ eV} = 1.6 \times 10^{-13} \text{ joules} \text{ OR } 1 \text{ joule} = 6.25 \times 10^{12} \text{ MeV}$$

Example

Take a helium-4 nucleus, for example. We know that the mass of two neutrons and two protons is 4.03188 amu:

$$\text{Mass of 2 neutrons} = (2) (1.008\,66 \text{ amu}) = 2.017\,32 \text{ amu}$$

$$\text{Mass of 2 protons} = (2) (1.007\,28 \text{ amu}) = 2.014\,56 \text{ amu}$$

$$\text{Total mass of } 2\text{ n} + 2\text{ p} = 4.031\,88 \text{ amu}$$

Furthermore, we can subtract the mass of two electrons from the experimentally measured mass of a helium-4 *atom* to find that the mass of a helium-4 *nucleus* is 4.001 50 amu

$$\text{Mass of helium-4 atom} = 4.002\,60 \text{ amu}$$

$$-\text{Mass of 2 electrons} = -(2) (5.486 \times 10^{-4} \text{ amu}) = -0.001\,10 \text{ amu}$$

$$\text{Mass of helium-4 nucleus} = 4.001\,50 \text{ amu}$$

Subtracting the mass of the helium nucleus from the combined mass of its constituent neutrons and protons shows a difference of 0.030 38 amu. That is, 0.030 38 amu (or 0.030 38 g/mol) is *lost* when two protons and two neutrons combine to form a helium-4 nucleus.

$$\text{Mass of } 2\text{ n} + 2\text{ p} = 4.031\,88 \text{ amu}$$

$$-\text{Mass of } {}^4\text{He nucleus} = -4.001\,50 \text{ amu}$$

$$\text{Mass difference} = 0.030\,38 \text{ amu} \quad (\text{or } 0.030\,38 \text{ g/mol})$$

Using the Einstein equation, we can calculate this binding energy for a helium-4 nucleus:

$$\begin{aligned}\Delta E &= \Delta mc^2 \quad \text{where } c = 3.00 \times 10^8 \text{ m/s} \\ &= (3.038 \times 10^{-5} \text{ kg/mol}) (3.00 \times 10^8 \text{ m/s})^2 \\ &= 2.73 \times 10^{12} \text{ kg} \cdot \text{m}^2 / (\text{mol} \cdot \text{s}^2) \\ &= 2.73 \times 10^{12} \text{ J/mol} = 2.73 \times 10^9 \text{ kJ/mol}\end{aligned}$$

To make comparisons among different nuclides easier, binding energies are usually expressed on a per-nucleon basis using *electron volts* (eV) as the energy unit, where 1 million electron volts. Thus, the helium-4 binding energy is 7.08 MeV/nucleon:

$$\begin{aligned}\text{Helium-4 binding energy} &= \left(\frac{2.73 \times 10^{12} \text{ J/mol}}{6.022 \times 10^{23} \text{ nuclei/mol}} \right) \left(\frac{1 \text{ MeV}}{1.60 \times 10^{-13} \text{ J}} \right) \left(\frac{1 \text{ nucleus}}{4 \text{ nucleons}} \right) \\ &= 7.08 \text{ MeV/nucleon}\end{aligned}$$

Consider the change in mass and energy for Cl-35 atoms.

The actual mass of a Cl-35 atom is 34.9689 amu. Comparing this to the total mass of its protons, neutrons and electrons shows a discrepancy (a mass deficiency) in the atom.

$$\text{protons:} \quad 17 \times 1.0073 \text{ amu} = 17.124 \text{ amu}$$

$$\text{neutrons:} \quad 18 \times 1.0087 \text{ amu} = 18.157 \text{ amu}$$

$$\text{electrons:} \quad 17 \times 0.00054858 \text{ amu} = 0.0093 \text{ amu}$$

$$\text{sum} = 35.290 \text{ amu}$$

$$\text{mass deficiency of a Cl-35 atom } (\Delta m) = 35.290 - 34.9689 = 0.321 \text{ amu}$$

$$\Delta m = \left(\frac{0.321 \text{ amu}}{\text{atom}} \right) \times \left(\frac{1 \text{ g}}{6.022 \times 10^{23} \text{ amu}} \right) \times \left(\frac{6.022 \times 10^{23} \text{ atoms}}{1 \text{ mol } ^{35}\text{Cl}} \right) = 0.321 \text{ g/mol of } ^{35}\text{Cl}$$

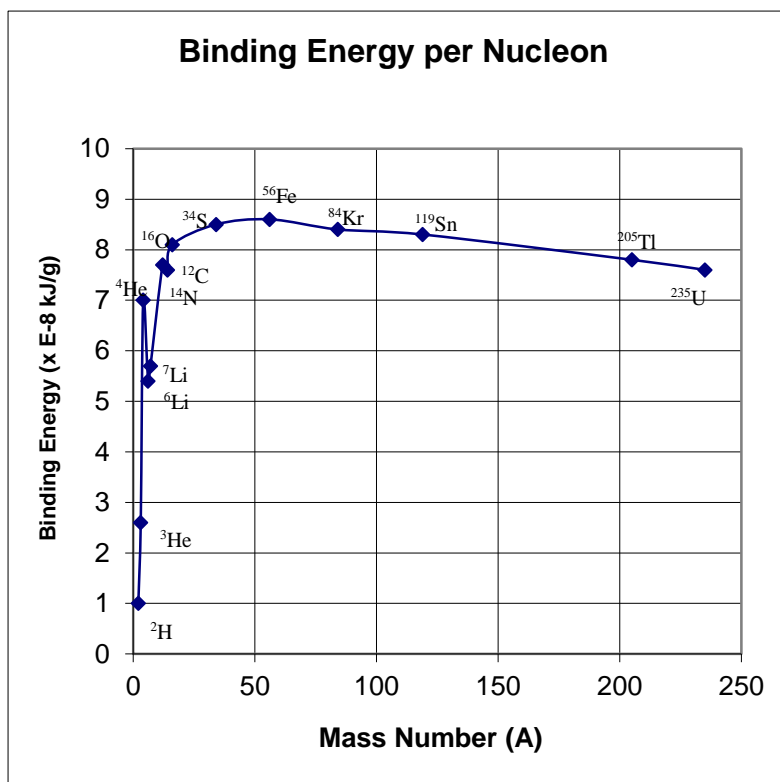
This is a significant mass difference, easily measured on a laboratory scale. The mass deficiency represents the amount of matter that would be converted into energy and released if the Cl-35 atom were produced by combining individual electrons, neutrons and protons. This energy is the **nuclear binding energy** and may also be stated as the amount of energy necessary to break a Cl-35 atom into its individual subatomic particles. The nuclear binding energy can be calculated from the mass deficiency using $\Delta e = \Delta mc^2$.

$$\Delta e = \Delta mc^2 \rightarrow \Delta e = (3.21\text{E-}4 \text{ kg/mol}) \times (3.00\text{E}8 \text{ m/s})^2 = 2.89\text{E}13 \text{ J/mol } ^{35}\text{Cl atoms}$$

Problem 11: Fe-56 is the most stable of all nuclides. Calculate its binding energy per mole.

An Fe-56 atom has a mass of 55.934939 amu.

Calculation of binding energy for various elements shows that binding energy per nucleon varies considerably, i.e., some nuclei are much more stable than others. The greater the binding energy per nucleon, the more stable is the nuclide. A plot of nuclear binding energy per nucleon vs. mass number shows important trends:



- i. Nuclides with < 10 nucleons have smaller binding energies; they have too few nucleons for optimum interaction.
- ii. ^4He is exceptionally stable, which is why it is emitted intact as an α particle.
- iii. Above $A = 12$, the binding energy per nucleon varies from -7.6 to -8.8×10^8 kJ/g.
- iv. Most importantly, binding energy per nucleon is maximum at ^{56}Fe . Up to this point, nuclides become more stable with increasing mass number, but the addition of more nucleons lowers stability.
- v. Some unstable radioactive nuclei emit a single proton, a neutron, or α particle as they decay in the direction of greater stability, however all nuclides are stable with respect to complete decomposition into separate protons and neutrons. None decomposes entirely into elementary particles.

The peak stability at Fe-56 suggests that there are two ways nuclides can increase their binding energy per nucleon:

- A heavier nucleus can split into lighter ones (close to $A = 56$) in a **fission** process, which releases large amounts of energy. Nuclear power plants generate energy through fission, as do atomic bombs.
- Lighter nuclei can combine to form a heavier one (closer to $A = 56$) in a **fusion** process, again releasing large amounts of energy. The sun and other stars generate energy

through fusion. In the hydrogen bomb and fusion reactors (being researched) hydrogen nuclei fuse to form the very stable He-4 nucleus.

Interaction of radiation with matter

Relative Strengths of Radiations (Molecular Movement, Excitation and Ionization):

- ❑ When low energy radiation, such as infrared collides with a substance, it is absorbed and the temperature of the substance rises, i.e., its kinetic energy increases; its molecular vibrations, rotations and translations increase.
- ❑ Radiation of intermediate energy, e.g., visible or UV, causes electronic *excitation*. For example, an apple appears red because its peel absorbs blue light, reflecting the red. The blue light that is absorbed has the correct energy to cause electrons to temporarily jump to higher energy levels.

These types of radiation are termed *nonionizing* radiation.

- ❑ High-energy radiation (γ rays) cause *ionization*. Electrons are completely dislodged from their atoms forming *ion pairs* (electrons and positive ions)

Units of Radiation Dose:

Unit	Quantity Measured	Description
Becquerel (Bq)	Decay events	Amount of sample that undergoes 1 disintegration/s
Curie (Ci)	Decay events	Amount of sample that undergoes 3.7×10^{10} disintegrations/s
Gray (Gy)	Energy absorbed per kilogram of tissue	1 Gy = 1 J/kg tissue
Rad	Energy absorbed per kilogram of tissue	1 rad = 0.01 Gy
Sievert (Sv)	Tissue damage	1 Sv = 1 J/kg
Rem	Tissue damage	1 rem = 0.01 Sv

Effects of Ionizing Radiation on Living Matter:

Nonionizing radiation is relatively gentle but ionizing radiation has harmful effects on living tissue. Ionizing radiation breaks bonds in cell membranes resulting in destruction of enzyme bonds, destruction of tissue around organs and alterations in nucleic acids in DNA (genetic damage).

We are continuously exposed to ionizing radiation from both natural sources (**background radiation**) and artificial sources. One source is cosmic radiation, which increases with altitude because of decreased atmospheric absorption.

However the soil is the source of most background radiation due to the presence of thorium and uranium minerals. Radon, the heaviest noble gas (Group 8A), is a radioactive product of uranium and thorium decay and its concentration in the air we breathe varies with type of local soils.

Moreover, about 150 g of K^+ ions is dissolved in the tissue water of an average adult and 0.0118% is radioactive K-40. The presence of these substances in addition to atmospheric $^{14}CO_2$ ensures that all food, water, clothing and building materials are slightly radioactive.

Some Properties of Ionizing Radiation

Type of Radiation	Energy Range	Penetrating Distance in Water*
α	3–9 MeV	0.02–0.04 mm
β	0–3 MeV	0–4 mm
X	100 eV–10 keV	0.01–1 cm
γ	10 keV–10 MeV	1–20 cm

* Distances at which one-half of the radiation has been stopped

Because of their relatively large mass, α particles move slowly (up to only one-tenth the speed of light) and can be stopped by a few sheets of paper or by the top layer of skin. Beta particles, because they are much lighter, move at up to nine-tenths the speed of light and have about 100 times the penetrating power of α particles. A block of wood or heavy protective clothing is necessary to stop β radiation, which would otherwise penetrate and burn the skin. Gamma rays and X rays move at the speed of light and have about 1000 times the penetrating power of α particles. A lead block several inches thick is needed to stop γ and X radiation, which could otherwise penetrate and damage the body's internal organs.

Data on health effects of radiation exposure is limited since it is only available from test animals, and victims of nuclear accidents and Japanese atomic bomb survivors. The following table lists acute health effects of single dose, whole body irradiations.

remS	Effect
5 - 20	possible chromosomal aberrations

20 - 100	temporary reduction in white blood cells
50 - 100	temporary sterility in men
100 - 200	‘mild radiation sickness’ – diarrhea, vomiting, reduced infection resistance, possible bone growth retardation in children
300+	permanent sterility in women
300 - 400	‘serious radiation sickness’ – marrow, intestine destruction
400 - 1000	acute illness, early deaths
3000+	acute illness, death in hours to days

DETECTING AND MEASURING RADIOACTIVITY

The fact that the human body cannot detect a lethal dose of ionising radiation has done much to raise apprehension in the public about this type of hazard.

In order to detect radiation we rely on devices that are based on the physical or chemical effects of radiation and they can be found in the following categories.

- (a) The ionization in gases
- (b) The ionization and excitation in certain solids
- (c) The changes in chemical systems
- (d) The activation by neutrons

Instruments used for the measurement of radiation fall into two classes; survey instruments and personal monitoring devices. The majority of survey instruments rely on detectors that utilise the ionisation of gases. Others use crystalline materials that react to gamma ray photons by producing a Compton effect electron or a photo-electron. Personal dosimeters rely on thermoluminescence, photographic or optical luminescence effects.

SURVEY INSTRUMENTS

The Ion Chamber

The interaction of radiation in a gas results in the production of ion pairs consisting of a negative ion (electron) and a positive ion. The ion chamber consists of a cylindrical chamber containing air at atmospheric pressure. A moderate voltage (100 volts) is applied between two electrodes, the anode and cathode. Ionizing radiation entering the chamber by a thin end window produces ion pairs and the negative ions are attracted to the positive electrode (anode) and the positive ions to the negative electrode (cathode). This flow of ions produces a small electric current which is a measure of the radiation dose rate, ie ionization produced per second.

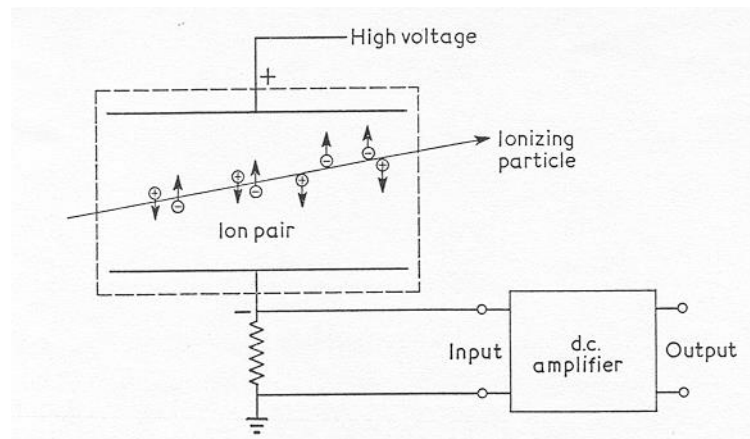


Figure 1: The Ion Chamber

The current produced in the ion chamber is very small ($\sim 10^{-12}$ amps) and therefore very sensitive amplification electronics is required making this type of monitor very expensive.

The ion chamber is the ideal instrument for measuring dose rate and cumulated dose in integrating models since the ionisation properties of air are similar to those of the elements in the human body. Ion chambers are not recommended for the measurement of surface contamination as they are relatively insensitive and have a moderately slow response time to the detection of ionizing radiation.

The Geiger-Muller Counter

If the voltage in an ionization system is increased beyond a certain point, an effect known as gas amplification occurs. The negative ions are now accelerated towards the anode and are of sufficient energy to cause further ionization themselves before reaching the anode.

If the voltage is increased further the gas amplification or avalanche effect is so great that a single ionizing particle produces a large pulse of current which can be converted by a simple rate meter to produce a click on a loudspeaker. The size of the pulse is the same regardless of the energy of the incident radiation.

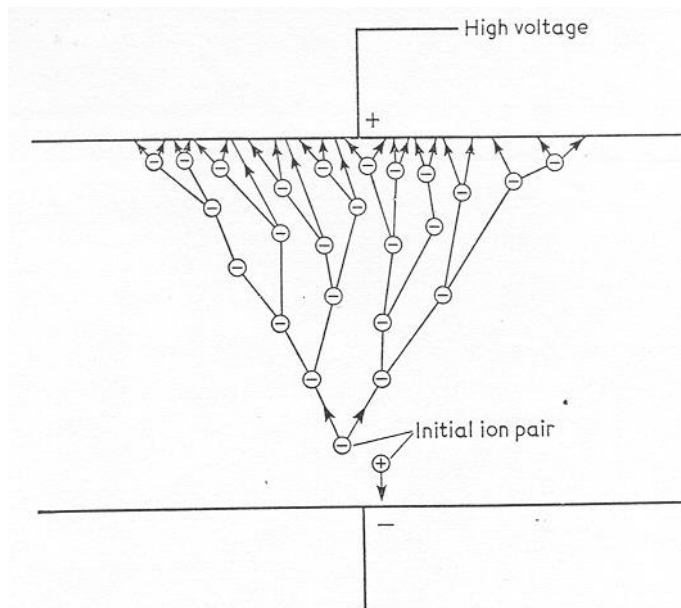


Figure 2: Gas amplification

The Geiger counter is normally constructed in a tubular form with the metal outer casing acting as the cathode and a thin wire running through the centre acting as the anode. There is a thin end window usually constructed of mica to allow soft beta particles to enter. Inside the tube the counter gas (normally 90% argon and 10% methane) is held at less than 1 atmosphere. The methane is there as a quenching agent to “mop” up the positive ions which would otherwise strike the cathode, releasing further electrons which would cause the counter to go into continuous discharge.

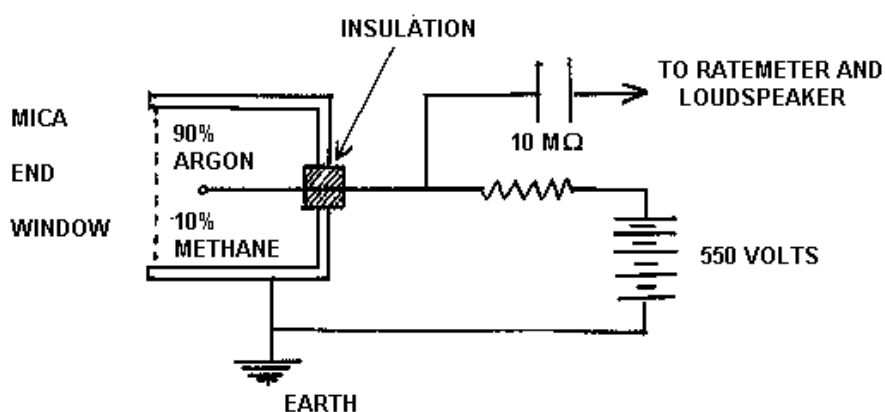


Figure 3: The Geiger-Müller counter

Modern counters now use halogen as a quenching agent as methane has a finite lifetime and halogen does not.

Solid State Detectors

The term solid state detectors refers to certain classes of crystalline substances which exhibit measurable effects when exposed to ionising radiation. In these substances electrons exist discrete energy bands separated by forbidden bands. The highest energy band in which electrons normally exist is the valence band. The transfer of energy from a photon or charged particle to a valence may raise it to through the forbidden band into the excitation band or the conduction band. The vacancy left behind by the electron is known as a hole and is analogous to a positive ion in a gas system.

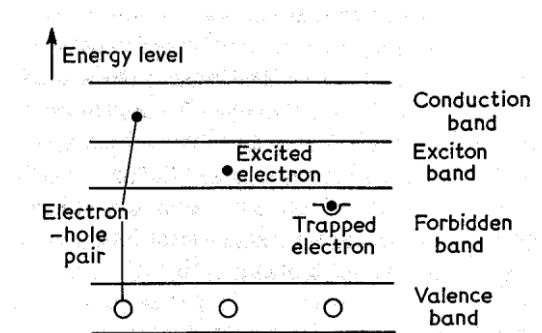


Figure 4: Ionisation, excitation and trapping

The three states shown above may be permanent or only exist for a short time depending on the material and temperature. In returning to the valence band the difference in energy is emitted as fluorescent radiation, normally a light photon.

The Scintillation Counter

Scintillation counters are based on detection of the fluorescent radiation emitted when an electron returns from an excited state to the valence band.

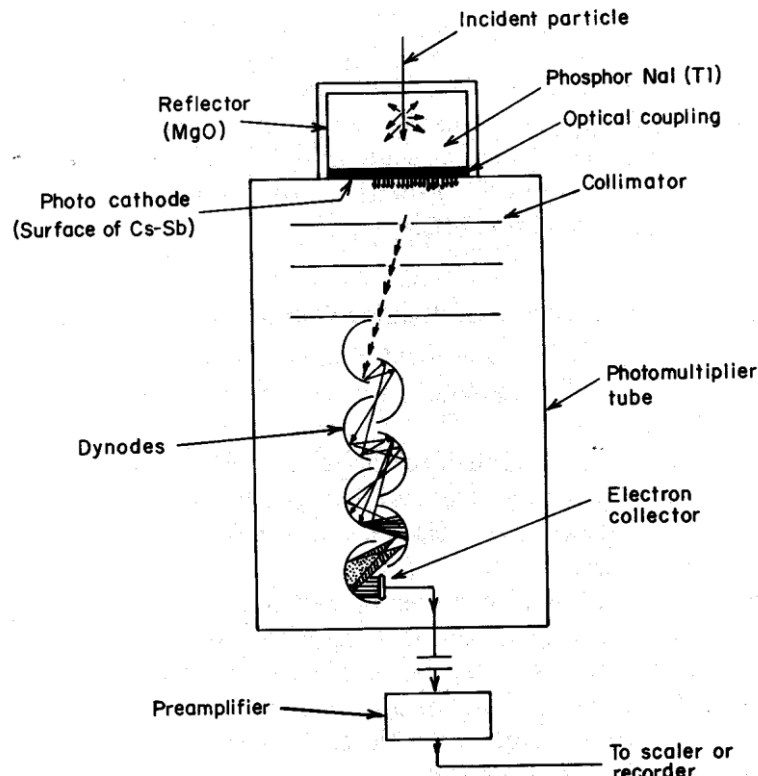


Figure 5: The scintillation counter

Most monitors use sodium iodide (NaI) as the scintillator as it only takes about $1 \mu\text{s}$ for the electron to return to the valence band. The absorption of 1 MeV gamma photon results in about 10,000 excitations and the same number of photons of light.

These scintillations are detected by the front face of a photomultiplier tube via optical coupling between the light tight can surrounding the NaI and the photo-cathode of the PM tube. The photo-cathode detects these very faint light signals and converts them into electrical pulses. The size of the pulse is proportional to the photon energy dissipated in the crystal.

PERSONAL MONITORING DEVICES

Thermoluminescent detectors

These detectors utilise the electron trapping process. One of the most common materials is lithium fluoride which is selected because after irradiation electrons in the crystal matrix are raised to a metastable excited state. Under normal temperatures these electrons remain in this state, but heating the material to over 200°C releases them from the traps and they rapidly return to the valence band with the emission of a light photon. If the device is heated in the dark in the presence of a photomultiplier tube the light photons can be measured and this is proportional to the radiation dose that the TLD badge received. Once these devices have been

“zeroed” they are rewrapped and reissued for further wear. Some of these devices can reach a considerable age and are expensive to replace if they are lost. Sometimes full zeroing does not take place and badges have been known to arrive at the customer already carrying a small apparent radiation dose. This can lead to problems when the wearer has been credited with a radiation dose which may be classed as penetrating and the only work carried out has been with beta emitters which would give a skin dose only.

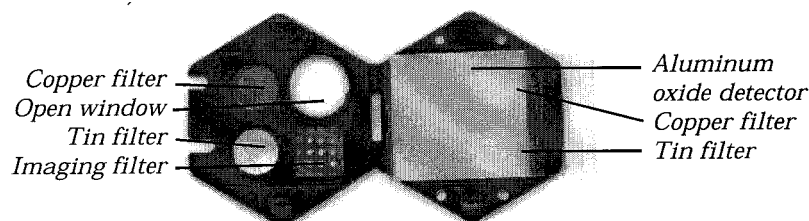
Film badge dosimeters

Ionising radiation reacts with photographic film in the same way as visible light ie, exposure to radiation blackens the film. Photographic film contains molecules of silver bromide that forms metallic silver when irradiated. When the film is developed the optical density is used to assess the dose that the dosimeter has received over a set wearing period. Film badge holders contain several filters to ascertain whether the dose received is whole body or skin.

Film badges can only be used once and therefore are much cheaper than TLD badges. They also arrive at the customer with a guaranteed zero dose which avoids the problems associated with TLD badges.

Optically stimulated luminescence (OSL) dosimeters

Optically stimulated luminescence dosimeters measure radiation exposure due to X-ray, gamma and beta radiation through a thin layer of aluminium oxide. After use, the aluminium oxide is stimulated with laser light causing it to fluoresce in proportion to the amount of radiation exposure. These devices are extremely sensitive and more accurate than TLD or film dosimeters.



The Luxel optically stimulated luminescence dosimeter

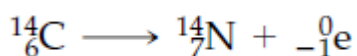
Applications of Nuclear Chemistry

I. Dating with Radioisotopes

Biblical scrolls are found in a cave near the Dead Sea. Are they authentic? Mummy is discovered in an Egyptian tomb. How old is it? The burned bones of a man are dug up near Lubbock, Texas. How long have humans lived in the area? These and many other questions can be answered by archaeologists using a technique called *radiocarbon dating*. (The Dead Sea Scrolls are 1900 years old and authentic, the mummy is 3100 years old, and the human remains found in Texas are 9900 years old.) Radiocarbon dating of archaeological artifacts depends on the slow and constant production of radioactive carbon-14 in the upper atmosphere by neutron bombardment of nitrogen atoms. (The neutrons come from the bombardment of other atoms by cosmic rays.)

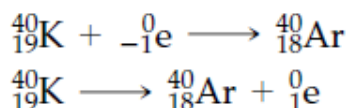


Carbon-14 atoms produced in the upper atmosphere combine with oxygen to yield ${}^{14}\text{CO}_2$ which slowly diffuses into the lower atmosphere, where it mixes with ordinary ${}^{12}\text{CO}_2$ and is taken up by plants during photosynthesis. When these plants are eaten, carbon-14 enters the food chain and is ultimately distributed evenly throughout all living organisms. As long as a plant or animal is living, a dynamic equilibrium exists in which an organism excretes or exhales the same amount of ${}^{14}\text{C}$ that it takes in. As a result, the ratio of ${}^{14}\text{C}$ to ${}^{12}\text{C}$ in the living organism is the same as that in the atmosphere— about 1 part in 10^{12} . When the plant or animal dies, however, it no longer takes in more ${}^{14}\text{C}$ and the ratio ${}^{14}\text{C}/{}^{12}\text{C}$ in the organism slowly decreases as ${}^{14}\text{C}$ undergoes radioactive decay by β emission, with $t_{1/2} = 5730$ years.



At 5730 years (one ${}^{14}\text{C}$ half-life) after the death of the organism, the ratio ${}^{14}\text{C}/{}^{12}\text{C}$ has decreased by a factor of 2; at 11,460 years after death, the ratio ${}^{14}\text{C}/{}^{12}\text{C}$ has decreased by a factor of 4; and so on. By measuring the present ${}^{14}\text{C}/{}^{12}\text{C}$ ratio in the traces of any once-living organism, archaeologists can determine how long ago the organism died. Human or animal hair from well-preserved remains, charcoal or wood fragments from once-living trees, and cotton or linen from once living plants are all useful sources for radiocarbon dating. The technique becomes less accurate as samples get older and the amount of ${}^{14}\text{C}$ they contain diminishes, but artifacts with an age of 1000–20,000 years can be dated with reasonable accuracy. The outer limit of the technique is about 60,000 years.

Just as radiocarbon measurements allow dating of once-living organisms, similar measurements on other radioisotopes make possible the dating of rocks. potassium-40 for example, has a half-life of 1.28×10^9 years and decays through electron capture and positron emission to yield argon-40. (Both processes yield the same product.)



The age of a rock can be found by crushing a sample, measuring the amount of ${}^{40}\text{Ar}$ gas that escapes, and comparing the amount of ${}^{40}\text{Ar}$ with the amount of ${}^{40}\text{K}$ remaining in the sample. It is through techniques such as these that the age of the earth has been estimated at approximately 4.5 billion years.

II. Medical Uses of Radioactivity

The origins of nuclear medicine date to 1901, when the French physician Henri Danlos first used radium in the treatment of a tuberculous skin lesion. Since that time, uses of radioactivity have become a crucial part of modern medical care, both diagnostic and therapeutic. Current nuclear techniques can be grouped into three classes:

(1) *in vivo* procedures, (2) therapeutic procedures, and (3) imaging procedures.

In Vivo Procedures *In vivo* studies—those that take place *inside* the body—are carried out to assess the functioning of a particular organ or body system. A radio-pharmaceutical agent is administered, and its path in the body—whether it is absorbed, excreted, diluted, or concentrated—is determined by analysis of blood or urine samples.

An example of the many *in vivo* procedures using radioactive agents is the determination of whole-blood volume by injecting a known quantity of red blood cells labeled with radioactive chromium-51. After a suitable interval to allow the labelled cells to be distributed evenly throughout the body, a blood sample is taken, the amount of dilution of the ${}^{51}\text{Cr}$ is measured, and the blood volume is calculated.

$$\text{Amount of } ^{51}\text{Cr} = C_0 \times V_0 = C_{\text{blood}} \times V_{\text{blood}}$$

$$\text{or } V_{\text{blood}} = \frac{C_0 V_0}{C_{\text{blood}}}$$

where: C_0 = Concentration of labeled cells injected ($\mu\text{Ci/mL}$)
 V_0 = Volume of labeled cells injected (mL)
 C_{blood} = Concentration of labeled cells in blood ($\mu\text{Ci/mL}$)
 V_{blood} = Blood volume

Therapeutic Procedures Therapeutic procedures—those in which radiation is used to kill diseased tissue—can involve either external or internal sources of radiation. External radiation therapy for the treatment of cancer is often carried out with γ rays from a cobalt-60 source. The highly radioactive source is shielded by a thick lead container and has a small opening directed toward the site of the tumor. By focusing the radiation beam on the tumor and rotating the patient's body, the tumor receives the full exposure while the exposure of surrounding parts of the body is minimized. Nevertheless, sufficient exposure occurs so that most patients suffer some effects of radiation sickness.

Internal radiation therapy is a much more selective technique than external therapy. In the treatment of thyroid disease, for example, iodine-131, a powerful β emitter known to localize in the target tissue, is administered internally. Because β particles penetrate no farther than several millimeters, the localized ^{131}I produces a high radiation dose that destroys only the surrounding diseased tissue.

Imaging Procedures Imaging procedures give diagnostic information about the health of body organs by analyzing the distribution pattern of radioisotopes introduced into the body. A radiopharmaceutical agent that is known to concentrate in a specific tissue or organ is injected into the body, and its distribution pattern is monitored by external radiation detectors. Depending on the disease and the organ, a diseased organ might concentrate more of the radiopharmaceutical than a normal organ and thus show up as a radioactive “hot” spot against a “cold” background. Alternatively, the diseased organ might concentrate less of the radiopharmaceutical than a normal organ and thus show up as a cold spot on a hot background. The radioisotope most widely used today is technetium-99m, whose short half-life of 6.01 hours minimizes a patient's exposure to harmful effects. Bone scans using Tc-99m, are an important tool in the diagnosis of cancer and other pathological conditions.

III. Research/Industrial Uses of Radionuclides

- a. Reaction mechanisms are studied using radioactive reagents. For example, the complex mechanism of photosynthesis was unraveled by Melvin Calvin over 7 years (Noble prize in 1961). $6\text{CO}_2 + 6\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$
- b. Chemists and engineers use radioactive tracers to study material movement in paint, metal plating, detergent action, etc. Hydrologic and meteorological engineers have used tracers to map deep ocean currents and atmospheric circulation during hurricanes.
- c. Engineers use radionuclides to measure the level of corrosive fluids in tanks where other level gages will not survive.
- d. *Neutron Activation Analysis* (NAA) is a chemical analytical tool. Neutrons bombard a non-radioactive substance, converting a small fraction of its atoms to radioisotopes, which exhibit characteristic decay patterns, such as γ ray spectra, that reveal the elements present. Unlike chemical analysis, the NAA is non-destructive, leaving the sample unharmed. Priceless art works are authenticated by evaluating paint/pigment in old paintings. NAA is also used in forensics to identify trace amounts of ammunition in a suspect's hand or trace amounts of arsenic in the hair of a poison victim. Automotive engineers use NAA to monitor friction and wear (metal transfers during friction) and hence evaluate various lubricants.

IV. Agricultural Uses of Radionuclides

- a. As an alternative to chemical pesticides, various insects (screw-worm fly, Mediterranean fruit fly in California and malaria carrying tsetse fly in the tropics) have been controlled using radioactivity. By irradiating (sterilizing) with γ rays and releasing large numbers of male flies, the populations of these insects has been greatly reduced. The sterilized males compete with unsterilized males in mating with females but produce no offspring.
- b. γ irradiation increases the shelf life of foods by killing microorganisms that cause food to spoil. The practice is controversial. Opponents suggest that irradiation might lower food value and produce harmful byproducts. The United Nations has approved irradiation for potatoes, wheat, chicken, and strawberries.

RADIOANALYTICAL METHODS

Nuclear analytical techniques deal with nuclear excitations, electron inner shell excitations, nuclear reactions, and/or radioactive decays. Nuclear Analytical Methods can be used for research activities on environmental studies like water quality assessment, pesticide residues, global climatic change (transboundary), pollution and remediation.

Radiochemical methods are of three types based on the origin of the radioactivity. In *activation analysis*, radioactivity is induced in one or more elements of the sample by irradiation with suitable radiation or particles (most commonly, neutrons from a nuclear reactor). The resulting radioactive emissions are then measured.

In the second category are methods in which the radioactivity is physically introduced into the sample by adding a measured amount of a radioactive species called a *tracer*. The most important quantitative methods based on introducing radiotracers are *isotope dilution* methods, in which a weighed quantity of radioactively tagged analyte having a known activity is added to a measured amount of the sample. After thorough mixing to assure homogeneity, a fraction of the component of interest is isolated and purified. The activity of the isolated fraction is then measured and used to calculate the mass of the component of interest in the original sample. Tracers are also used by organic and inorganic chemists to elucidate reaction mechanisms. The third class of methods involves measurement of naturally occurring radioactivity in a sample. Examples of this type of method are the measurement of radon in household air and uranium in pottery and ceramic materials.

A. RADIOTRACER TECHNIQUES

A radiotracer is defined as a chemical specie having one or more radionuclides as cation, anion or one of its components so that it may be used as a marker to follow the course of a chemical reaction or physical process or to show the location of a substance in an area. The activity of radionuclide is monitored to follow the process under investigation. Basic principle, on the basis of which a radiotracer works, is that it mixes well with its own element or compound and behaves chemically in a similar manner except for its radiation emitting property. Radiotracers can be used qualitatively for identification only, as simple markers or to quantitatively determine the amount of a component in a mixture.

Isotope Dilution Analysis (IDA)

It is a widely used quantitative analytical technique of considerable value in complex mixtures of compounds in organic syntheses, biochemical systems and for the determination of inorganic elements in geological and biological samples. It has the advantage of not requiring the separation of a component to be determined quantitatively from an analyte mixture. The method of IDA has two alternatives, direct isotope dilution analysis (DIDA) and inverse/reverse isotope dilution analysis (I/RIDA).

Principle of IDA

It is primarily based on the principle that the specific activity of a mixture of stable and radioisotope remains unchanged during chemical processing. Accurately known amount of specific activity of a radiotracer is added to an aliquot of analyte mixture containing the sought component. After addition, the resultant specific activity decreases. Chemical separation procedure is carried out where the component need not be recovered quantitatively but it must be in chemically pure form with well defined composition and in sufficient amount so that it can be weighed. Separation may be carried out by any of the following separation procedures:

- i. Solvent extraction of chelate complexes formed with specific reagent
- ii. Precipitation using specific reagent
- iii. Ion-exchange separation
- iv. Electrodeposition or sorption process

After equilibration the desired constituent is separated, weighed and its activity is measured.

Advantages and Limitations of IDA

As already mentioned radiotracers have special advantages compared to routine chemical or instrumental methods of analysis. Some special advantages of IDA are;

- i. Isotope dilution analysis is more sensitive than many other analytical methods depending on the availability of radiotracer of desired specific activity. For certain elements such as Zn, Ag, Hg, IDA has better detection limits than even neutron activation analysis. Of course sensitivity of IDA technique depends on the availability of carrier free or high specific activity radiotracer.
- ii. Where other instrumental methods fail to achieve these limits for complex matrices, IDA using appropriate radiation detectors can measure much smaller amounts.

- iii. Radiotracers also have potential specificity due to their unique decay properties and hence chemical interferences are of little consequence.
- iv. Quantitative separation is not necessary. In many wet chemical analyses involving trace amounts, it is almost impossible to achieve quantitative yield. However, yield should be more than 50% without too many losses.
- v. Nuclear detection equipments used for IDA are less expensive than many modern instruments. Instrumentation is quite simple because only gross activity measurement is required.
- vi. IDA can be used for speciation studies in environmental and biological samples.
- vii. Decay process of radiotracers is not affected by ambient conditions of temperature, concentration of reagents, pH, etc and these could be used for determining dyes in natural water systems.

Besides advantages, IDA has following limitations;

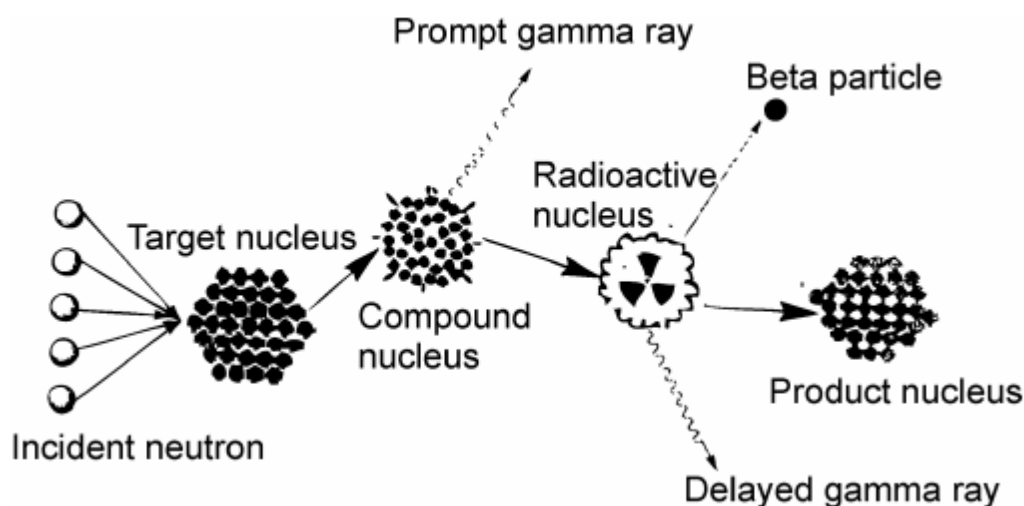
- i. IDA is essentially a destructive method. Since the sample is not preserved, it has a limited applicability.
- ii. The method can be used for the determination of a single element at a time whereas for several samples multielemental methods are preferred.
- iii. IDA has limited applicability for the elements for which suitable radiotracers are available.

B. ACTIVATION ANALYSIS (AA)

Techniques of activation analysis include the use of nuclear reactions induced by neutrons, photons or charged particles such as protons, deuterons, alpha particles and other heavy ions in a nuclear reactor or accelerator facility to produce radionuclides. When a target element is bombarded with a neutron beam, a compound nucleus with higher mass number in excited state is formed. It may undergo instantaneous decay to form a product nucleus finally emitting delayed β or γ rays. This technique is called neutron activation analysis (NAA). However, if the bombarding particle is photon, it is called photon activation analysis (PAA) or if the sample is bombarded with charged particles such as protons, deuterons or alpha particles then it is called charged particle activation analysis (CPAA). If bombarding particle induces x-ray emission via interaction with the electron shells of the target element, the analytical method is known as particle induced x-ray emission (PIXE). Of all the activation analysis methods, NAA using reactor neutrons remains the most widely used analytical method.

Principle of NAA

The technique of NAA involves two steps; irradiation of a sample with neutrons and subsequent measurement of the induced radioactivity. The radionuclides are characterized by their characteristic γ -ray energy and half-life as illustrated in the figure below



In neutron activation analysis the sample is kept in a neutron flux for a length of time that is sufficient to produce radionuclide product(s) in amounts that can be measured with the desired statistical precision.

One of the important advantages of NAA is its applicability to almost all elements in the periodic table. Other advantages of neutron activation are that it is non-destructive, has high sensitivity, minimal sample preparation procedures and ease of calibration. Consequently, NAA is an important technique for analyzing archaeological and forensic samples, as well as works of art.

In comparison with most other analytical techniques, radiochemical methods are usually more expensive and require more time to complete an analysis. Radiochemical methods also are subject to significant safety concerns due to the analyst's potential exposure to high-energy radiation and the need to safely dispose of radioactive waste.

Nuclear Fission and Electric Power Plants

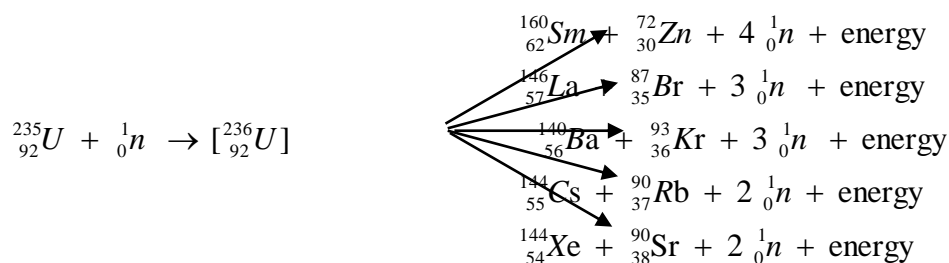
In a typical nuclear fission process, a neutron collides with a large atom, such as uranium-235, and forms a much less stable nuclide that spontaneously decomposes into two medium sized atoms and 2 or 3 neutrons. For example, when uranium-235 atoms are bombarded with

neutrons, they form uranium-236 atoms, which decompose to form atoms such as krypton-95 and barium-138 as well as neutrons.

Some smaller fissions are spontaneous, but some nuclides (especially larger ones) require that the activation energy be supplied (by neutron bombardment). Experiments with particle accelerators have shown that every element with $Z > 80$ has one or more isotopes capable of undergoing fission, provided they are bombarded at the right energy.

- Nuclei with atomic numbers between 89 (actinium) and 97 (berkelium) fission spontaneously with long half-lives of 10^4 to 10^7 years.
- Nuclei with atomic numbers of 98 (californium) or more fission spontaneously with shorter half-lives of a few milliseconds to 61 days.
- All known nuclides with mass numbers greater than 250 fission spontaneously because they are too big to be stable.

The $^{235}_{92}\text{U}$ nucleus can split in many different ways giving rise to various product nuclei. Neutron bombardment results in a highly excited U-236 nucleus, which splits apart in 10^{-14} seconds. The products are two nuclei of unequal mass and several neutrons (average of 2.4) and a large amount of energy.



A single U-235 nucleus releases 3.5×10^{-11} J when it splits; a mole of U-235 (about $\frac{1}{2}$ lb) releases 2.1×10^{13} J - a billion times as much energy as burning $\frac{1}{2}$ lb of coal (about 2×10^4 J).

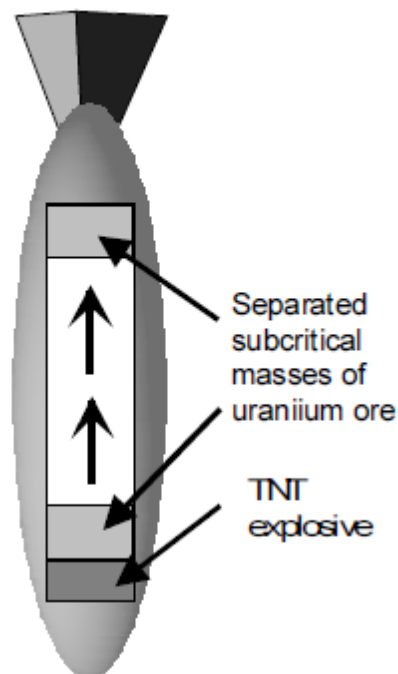
The two or three neutrons released per U-235 atom fissioned can collide with other nuclei causing them to split, releasing more neutrons and more energy. If the piece of uranium is large enough, product neutrons strike another fissionable nucleus before flying out of the sample. In this case, the reaction is self-sustaining (**a chain reaction**). The mass needed to achieve a chain reaction is the **critical mass**. If the sample has less than this mass (*subcritical*), most of the product neutrons leave the sample before colliding with another U-235 nucleus and a chain reaction does not occur.

Uncontrolled Fission: The Atomic (Nuclear) Bomb

An uncontrolled chain reaction may become explosive, as the world first learned in World War II. In August 1945, the United States detonated two atomic bombs over Japan. The horrible destructive power of these bombs was a major factor in the surrender of Japan a few days later.

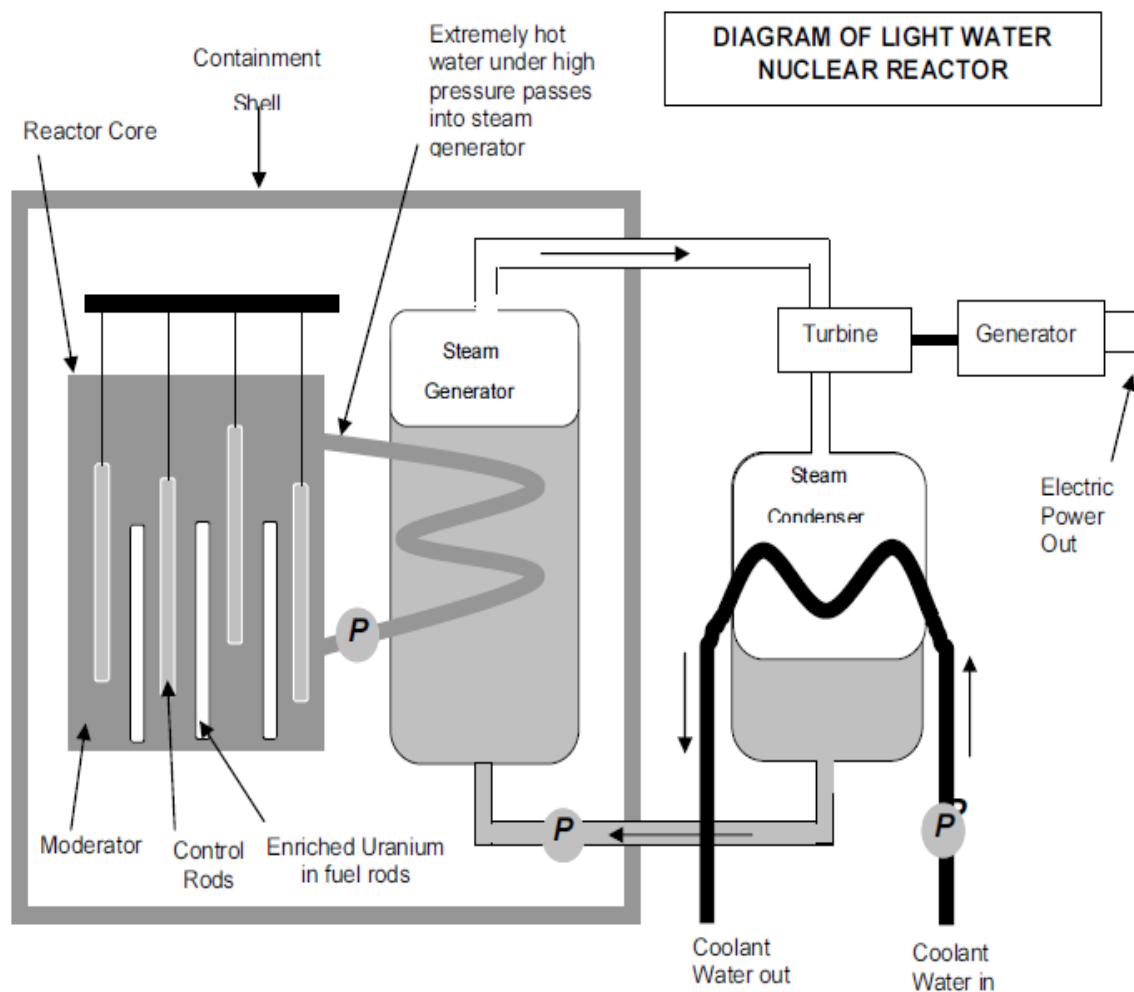
In an atomic bomb, a small explosion of trinitrotoluene (TNT) brings subcritical masses of fissionable material together, the critical mass is exceeded and the ensuing chain reaction brings about the nuclear explosion. The proliferation of nuclear power plants, which use fissionable materials to generate energy for electricity, has increased concern that more countries will have access to material for bombs. Only 1 kg of fissionable uranium was used in the first of the bombs dropped on Japan.

Atomic Bomb



Controlled Fission-Nuclear Energy Reactors:

Controlled fission can produce clean, plentiful electric power. Like a coal-fired power plant, a nuclear power plant generates heat to produce steam, which turns a turbine attached to an electric generator. In a coal plant, the heat is produced by burning coal; in a nuclear power plant by splitting uranium.



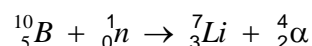
Most commercial nuclear power plants in the United States are ‘light water’ reactors, moderated and cooled by ordinary water. As shown in the diagram, a fission reactor consists of five main components: (1) fuel, (2) moderator, (3) control rods, (4) cooling system, and (5) shielding.

Fuel:

Rods of U_3O_8 enriched in U-235 and enclosed in tubes of a corrosion-resistant zirconium alloy serve as a fuel. Uranium ores naturally contains 0.7% U-235, the balance is nonfissionable U-238. This is enriched up to 3% to 4% U-235 needed to sustain a chain reaction. Enrichment is achieved after separating gaseous $^{235}\text{UF}_6$ from $^{238}\text{UF}_6$ prepared from the ore. The separation is by diffusion, the heavier molecules being slower moving. Another process uses an ultracentrifuge to separate particles of differing density.

Control Rods:

Sandwiched between the fuel rods are moveable *control rods* made of cadmium or boron steel, substances that absorb neutrons efficiently.



When the control rods are lowered, the chain reaction slows as fewer neutrons bombard the uranium fuel rods. When the control rods are raised, the chain reaction speeds up.

Moderator:

Flowing around the fuel and control rods in the reactor core is the *moderator*, a substance that slows the neutrons, making them better at causing fission than the fast ones emerging from the uranium fuel. The best moderators are comparable in mass to the neutrons. Helium is most efficient, slowing neutrons without absorbing them. The next most efficient is heavy water, deuterium oxide (${}^2\text{H}_2\text{O}$ or D_2O). Heavy water is expensive and so is used mostly in research reactors and in the Canadian built ‘CANDU Reactors’. Light water (${}^1\text{H}_2\text{O}$) is the most common moderator in American reactors. It is less efficient in that it absorbs some neutrons but light water is inexpensive.

Cooling Systems:

Two cooling systems are needed. First, the moderator itself serves as a coolant for the reactor. It transfers fission-generated heat to a steam generator. This converts water to steam. The steam then goes to turbines that drive generators to produce electricity. Another coolant (river water, seawater, or recirculated water) condenses the steam from the turbine, and the condensate is then recycled into the steam generator.

Shielding (Containment Shell):

The entire reactor is enclosed in a steel containment vessel. This is housed in a thick-walled concrete building. The operating personnel are further protected by a thick organic shield that is made of compressed wood fibers. This absorbs neutrons and beta and gamma rays that would otherwise be absorbed by the human body.

Dangers of Nuclear Reactors:

The fuel of nuclear reactors has neither the composition nor the extreme compactness of the critical mass of a bomb. Thus, no possibility of nuclear explosion exists.

The greatest danger is the possibility of a ‘*meltdown*’ of the reactor core. If, for example, the coolant circulation fails or is shut down too quickly after lowering the control rods, the fuel

elements may overheat and melt. Such operational errors and mechanical failures have resulted in reactor core meltdowns and release of radioactive gases and debris into the atmosphere at the Three-Mile Island facility in Pennsylvania in 1979 and at the Chernobyl plant in Ukraine of the former Soviet Union in 1986. Thousands of people living near Chernobyl may yet develop cancer from radiation exposure.

The moderator and its coolant are completely separate. The water from the steam generator is completely recycled so barring leaks, no radioactivity should find its way into the external water system (lake, river or sea). The cooling water being discharged to the environment is several degrees warmer than the intake and this *thermal pollution* is cited as upsetting the natural ecosystem, however, coal and gas fired generating facilities also cause thermal pollution.

A more serious problem is one of *nuclear waste disposal*. Operating a nuclear reactor for a few weeks produces lethal amounts of ^{90}Sr and ^{137}Cs equivalent to those produced by the explosion of an atomic bomb. Many of the fission products formed in nuclear reactors have long half-lives, and no satisfactory plan for their permanent disposal has been devised. Long-lived radionuclides from spent fuel must be stored underground in heavy, shock-resistant containers until they have decayed to the point that they are no longer biologically harmful. As examples, Sr-90 ($t_{1/2} = 28$ yr) and plutonium-239 ($t_{1/2} = 24,000$ yr) must be stored for 280 and 240,000 years, respectively, before they lose 99.9% of their activities. Critics of nuclear energy contend that the containers could corrode over such long periods, or burst as a result of earth tremors, and that transportation and reprocessing accidents could cause environmental contamination with radionuclides.

The potential for theft also exists. Plutonium-239, a fissionable product could be stolen from reprocessing plants and used to construct atomic weapons. Neutrons are the worst problem of radiation. The human body contains a high percentage of H_2O , which absorbs neutrons very efficiently. A new weapon, the *neutron bomb*, produces massive amounts of neutrons and so is effective against people, but it does not produce long-lasting radiation of the fission atomic bomb.

Advantages of Nuclear Reactors

Proponents of development of nuclear energy argue that advantages far outweigh the risks. Nuclear energy plants do not pollute the air with oxides of sulfur, nitrogen, and carbon or particulate matter as fossil fuel electric power plants do.

An advantage of nuclear fuels is the enormous amount of energy liberated per unit mass of fuel. At present, nuclear reactors provide about 17% of the electrical energy consumed in the United States. In some parts of Europe, where natural resources of fossil fuels are scarcer, up to 65% of electrical energy is produced from nuclear reactors, e.g., France and Belgium. With rapidly declining fossil fuel reserves and increasing energy demand, nuclear energy may become increasingly important.

Radioactive Waste

Radioactive wastes are the leftovers from the use of nuclear materials for the production of electricity, diagnosis and treatment of disease, and other purposes.

High-level radioactive waste consists of “irradiated” or used nuclear reactor fuel (i.e., fuel that has been used in a reactor to produce electricity). The used reactor fuel is in a solid form consisting of small fuel pellets in long metal tubes.

Mill tailings wastes are the residues remaining after the processing of natural ore to extract uranium and thorium. Commercial radioactive wastes that are not high-level wastes or uranium and thorium milling wastes are classified as low level radioactive waste. The low-level wastes can include radioactively contaminated protective clothing, tools, filters, rags, medical tubes, and many other items.

Nuclear power is characterized by a very large amount of energy available from a very small amount of fuel. Although the amount of nuclear waste (often referred to as radwaste) is relatively small, much of it is highly radioactive and must therefore be carefully managed as hazardous waste. The problems and solutions of nuclear waste disposal are becoming a major concern in the 21st Century. Many nuclear power plants, particularly in the developed countries around the world, are nearing the end of their operating lives. The end of the cold war has left us with radioactive waste from decommissioned nuclear missiles. Nuclear power is the only energy industry which takes full responsibility for all its wastes. The cost of waste disposal is included in the cost of the power produced.

Nuclear waste comprises a variety of materials requiring different types of management to protect people and the environment. One of the factors in managing nuclear wastes is the time that they are likely to remain hazardous. This depends on the kinds of radioactive isotopes in them, and particularly the half lives characteristic of each of those isotopes. The half-life is the time it takes for a given radioactive isotope to lose half of its radioactivity. After four half lives the level of radioactivity is 1/16th of the original and after eight half-lives 1/256th.

The various radioactive isotopes have half-lives ranging from fractions of a second to minutes, hours or days, through to billions of years. Radioactivity decreases with time as these isotopes decay into stable, non-radioactive ones.

The rate of decay of an isotope is inversely proportional to its half-life; a short half-life means that it decays rapidly. Hence, for each kind of radiation, the higher the intensity of radioactivity in a given amount of material, the shorter the half-lives involved.

Three general principles are employed in the management of radioactive wastes:

- a. concentrate-and-contain
- b. dilute-and-disperse
- c. delay-and-decay

The first two are also used in the management of non-radioactive wastes. The waste is concentrated and then isolated, or it is diluted to acceptable levels and then discharged to the environment. Delay-and-decay however is unique to radioactive waste management; it means that the waste is stored and its radioactivity is allowed to decrease naturally through decay of the radioisotopes in it.

The problem of nuclear-waste disposal is not as much technical as one that requires efficient management. Each country is ethically and legally responsible for its own nuclear wastes, therefore the default position is that all nuclear wastes will be disposed of in each of the 40 or so countries concerned. This means that countries like Sweden or Switzerland, which have only a few plants, still have to do the research and development and find a local site for disposal. This makes no economic or environmental sense at all. A better solution would be to have competitive, commercial geologic repositories -- in stable underground sites like the one in Yucca Mountain, Nevada -- that take waste from other countries for a fee. Plutonium, one of the most radioactive materials, does not move significantly in ground water, and if some did ultimately escape it would be readily detected, and measures could then be taken to avoid contamination. A geologic repository would work effectively for at least 100,000 years, after which the waste would be little more radioactive than the natural uranium from which it was derived.

According to the amount and type of radioactivity in them, nuclear waste materials can generally be classified under two categories – a) low level nuclear waste and b) high level nuclear waste.

- a) **Low level nuclear waste** usually includes material used to handle the highly radioactive parts of nuclear reactors (i.e. cooling water pipes and radiation suits) and waste from

medical procedures involving radioactive treatments or x-rays. Low-level waste is comparatively easy to dispose of. The level of radioactivity and the half-life of the radioactive isotopes in low-level waste are relatively small. Storing the waste for a period of 10 to 50 years will allow most of the radioactive isotopes in low-level waste to decay, at which point the waste can be disposed of as normal refuse.

Low-level nuclear waste is generated from hospitals, laboratories and industry, as well as the nuclear fuel cycle. It comprises paper, rags, tools, clothing, filters etc., which contain small amounts of mostly short-lived radioactivity. It is not dangerous to handle, but must be disposed of more carefully than normal garbage. Some low-level waste viz., resins, chemical sludges and reactor components, as well as contaminated materials from reactor decommissioning may require special shielding before disposal. Low-level nuclear waste is usually buried in shallow landfill sites. To reduce its volume, it is often compacted or incinerated (in a closed container) before disposal. Worldwide it comprises 97% of the volume but only 5% of the radioactivity of all nuclear waste.

- b) **High level nuclear waste** may be the spent fuel itself, or the principal waste from reprocessing this. It is generally material from the core of a nuclear reactor or nuclear weapon. This waste includes uranium, plutonium, and other highly radioactive elements formed during fission. Most of the radioisotopes in high level waste emit large amounts of radiation and have extremely long half-lives (some longer than 100,000 years) requiring long time periods before the waste will settle to safe levels of radioactivity. While only 3% of the volume of all radwaste, it holds 95% of the radioactivity. It contains the highly radioactive fission products and some heavy elements with long-lived radioactivity. It generates a considerable amount of heat and requires cooling, as well as special shielding during handling and transport. If the spent fuel is reprocessed, the separated waste is vitrified by incorporating it into borosilicate (Pyrex) glass, which is sealed inside stainless steel canisters for eventual disposal deep underground.

As can be readily appreciated from the foregoing, disposal of the high level nuclear waste is more problematic than the low level one. This article describes some of the methods that can/are being undertaken for dealing with this problem. The methods of nuclear waste disposal include:

1. Short Term Storage
2. Long Term Storage
3. Transmutation is currently being evaluated for long-term storage of nuclear waste.

1. Short Term Storage of Nuclear Waste

Radioactive material decays in an exponential fashion. Short-term storage will reduce the radioactivity of spent nuclear fuel significantly. A ten-year storage can bring a 100 times decrease in radioactivity. A further reduction of radioactive emissions, similar to that of the first 10 years, would take another 100 years of storage. Storing the waste for at least 10 years is recommended. The reduction in radioactivity during short-term storage makes handling and shipment of the waste much easier. After short term storage the waste will be sent for transmutation or long-term storage.

2. Long Term Storage for High Level Radioactive Waste

While there are methods of significantly reducing the amount of high-level radioactive waste, some (or all) high level radioactive waste must end its journey in long-term storage. Because "long term" refers to a period of thousands of years, security of the radioactive waste must be assured over geologic time periods. The waste must not be allowed to escape to the outside environment by any foreseeable accident, malicious action, or geological activity. This includes accidental uncovering, removal by groups intending to use the radioactive material in a harmful manner, leeching of the waste into the water supply, and exposure from earthquake or other geological activity. In addition, this security must be maintained over a period of time during which, not only will the designers of the storage area die, but also the host country will, in all likelihood, see different political regimes.

Civilization has undergone tremendous changes in the last 3000 years since the Egyptian Empire, yet some high level radioactive waste will take over 20,000 years to decay to safe levels.

Posing further difficulty is the fact that some of this waste is plutonium, and other actinide elements, produced as by-products of uranium fission. These elements are not only highly radioactive, but highly poisonous as well. The toxicity of plutonium is among the highest of any element known.

Areas currently being evaluated for long-term storage of nuclear waste are:

- a. Space
- b. Under the sea bed, and
- c. Large stable geologic formations on land

Long-term storage on land seems to be the favorite of most countries.

A. Disposal of Nuclear Waste in Space

Outer space is the most appropriate long-term storage option for high-level nuclear waste. This would ensure it's safe removal from humans regardless of the activities of nature or man on earth.

Anybody accidentally stumbling upon this waste would be at a lesser risk as they would be using radioactive shielding for space travel. Delivery of the waste into space has a crippling drawback --the rocket used to deliver the waste into space would need to provide enough power to escape the earth's gravity. This is necessary for two reasons: a) to leave the waste in orbit creates space garbage that is likely to reenter the earth's environment at some time due to collision with satellites and other orbiting waste or spacecraft; and b) the large delivery rocket would be expensive and an accident during launch could have catastrophic results. Space disposal therefore, will not be a viable option until space travel is considerably safer and less expensive.

b) Storage of Radioactive Waste in the Sea Bed

A possibility for long-term storage on the earth is burial in the seabed. The rock formations in the seabed are generally more stable than those on land reducing the risk of exposure due to seismic activity. Apart from this, there is little groundwater circulation under the seabed, reducing the possibility of radioactive material contaminating ground water available for human consumption.

The greatest appeal of under sea burial is also its greatest drawback. The enormous cost and difficulty of excavating the waste would likely prevent accidental or malicious disturbing of the waste. This cost is also keeping us from burying the waste at sea.

c) Long Term Storage of Radioactive Waste on Land

Long term storage in tectonically stable rock formations on land is the most likely solution for high-level radioactive waste. The radioactive material may be vitrified¹ and buried in caverns, created in a large rock formation. When use of the storage area is complete, it would be sealed again with stone. While still extremely expensive, and considerably unsafe, this is the most viable storage option currently available. Using methods that reduce the amount of radioactive waste could further enhance safety levels.

While most countries should not only be able to find suitably safe sites in stable geological formations, they should also demonstrate this safety so as to create public confidence. This is best achieved where there is simple geology.

3. Transmutation

Transmutation is the transformation of one element into another. The goal of transmutation, in radioactive waste disposal, is to transmute long half-life, highly radioactive elements, into shorter half-life, less-radioactive elements. There are two methods currently proposed for the transmutation of high-level radioactive waste are:

- a) Fast consumer reactors, and
- b) Hybrid reactors

a) Fast Consumer Reactors

Fast consumer reactors are merely variations of fast breeder reactors. These reactors take the plutonium created by nuclear reactors as byproduct, or as fuel for nuclear weapons and "consume" it. This process leaves uranium and other less dangerous radioactive waste. As an added benefit, the isotopes of the elements created as byproducts generally have shorter half-lives than the initial plutonium used as fuel.

b) Transmutation with a Hybrid Nuclear Reactor

Hybrid nuclear reactors promise near complete transmutation of almost any high level radioactive waste. The general process is to produce a sub-critical nuclear reactor (i.e. the nuclear reactions would stop under normal conditions) and bombard the reactor fuel with neutrons. The neutrons break apart the large radioactive elements, releasing energy. This energy is used to power the neutron source needed to start the fission reaction. There will be some high level radioactive waste produced (generally parts of the neutron source) but in comparison to the amount of radioactive waste consumed, this will be minimal. This high level waste will need to be placed in long-term storage.

NUCLEAR / RADIATION ACCIDENTS, INCIDENTS AND EVENTS

Nuclear Accidents: Causes are not deliberate, malicious, or malevolent. True accidents can be viewed as acts of nature or acts of god, but likely include failures of equipment and systems.

Nuclear Incidents: Causes can include deliberate actions but these are generally non-malicious and non-violent; may be due to poor judgment, wrong information coupled with malfunctions or other accident conditions, etc.

Nuclear Terrorism: A form of political violence that is designed to induce terror and psychic fear through the violent victimization and damage of noncombatant targets. These events

usually exploit the media in order to achieve maximum attainable publicity as an amplifying force. Massive economic damage is possible and is usually an intended outcome while substantial (or any) radiation injury to persons may or may not be involved.

The Major Recognized Categories of Accidents and Incidents:

Industrial radiography

High activity ^{192}Ir sources are typically used to radiograph welds in pipes. Portable radiography devices are often used with little training and little enforcement about good radiation protection practices. Extremely high, localized doses can result from improper handling and use of sources.

Industrial irradiation facilities

Facilities use intense radiation sources for sterilization of foods, surgical instruments, and other items. Unintended exposures result from radiation sources not properly returning into shields or failures of staff to know sources are deployed.

Medical procedures (primarily associated with therapy)

Accidents and incidents are generally over-exposures due to equipment malfunctions, lack of proper training, poor judgment or combinations.

Serious overexposures leading to acute radiation effects occur more often in therapeutic procedures while modest overexposures leading to increases in cancer risk probably occur more often in diagnostic procedures.

Overexposures range from a few times larger than appropriate in diagnostic imaging to levels causing severe acute effects.

Loss of control of radiation sources

“Orphaned sources” is a problem worldwide due to lack of record keeping on source owners and locations of use, little regulation on stewardship, and lack of institutional memory and controls.

Since 1983, there have been about 60 known incidents of radiation sources being lost, melted down, and usually reformed into steel bar construction materials.

Nuclear testing-related activities

A case example is testing of about 100 nuclear devices from 1951 to 1962 in the atmosphere at the Nevada Test Site (NTS) exposed military and public.

Only a few accidents at the NTS are known of but, in retrospect, testing resulted in unintended exposure of 160 million persons to 20 mGy on average.

Nuclear energy (fuel production, fuel storage, nuclear power plant operation)

Nuclear energy-related accidents involve more than operating reactors, though those are probably the most well known.

Other nuclear energy-related exposures have occurred among workers at facilities and among the public exposed to emissions from those facilities. These circumstances include facilities in the U.S., Russia (Mayak, Techa River), Japan (Tokaimura) and elsewhere

Terrorism

A form of political violence using radiation and/or radioactive materials that is designed to induce terror and psychic fear through the violent victimization and damage of noncombatant targets. Fortunately, the number of events to-date have been few, but the likelihood of future events is depressingly likely.

Some notable nuclear accidents and incidents

1. Hiroshima and Nagasaki

Unlike the many nuclear accidents that have occurred over the past century, America's decision to flatten Hiroshima and Nagasaki in 1945 killed upwards of a hundred thousand people, ended a war, and ignited an arms race that has slowed but not ended.

2. Chernobyl

The most famous name in nuclear power plant disasters is near the top of the list for a reason: The nearby city of Pripyat is still contaminated. Late on the night of April 26th, 1986, a pair of engineers at the Chernobyl nuclear power plant started running a torture test, to find out what would happen if the reactor lost most of its power supply. It went horribly wrong, and became the worst nuclear accident in human history. Before the test, the engineers pulled too many control rods out of the reactor core. Those graphite poles act like brakes, slowing nuclear reactions. With the rods out, and power to the reactor steadily decreasing, the plant was poised

for a catastrophe. Steam built up in the cooling system and there was a power spike, followed by an explosion. Someone pushed an emergency shutdown button, which automatically sent the control rods back into the reactor core. That was a mistake. It caused the reactor to overheat further. Eventually, the control rods caught fire, sending a shower of radioactive smoke over a wide swath of Europe and turning the nearby city of Pripyat, Ukraine into a nuclear wasteland. Within the plant, radiation levels climbed so high that some of the workers got a fatal dose within minutes. By some estimates, the disaster cost four thousand lives.

3. Hanford Nuclear Site

Over the course of several decades, the morons at Hanford Nuclear Site in Washington state accumulated massive amounts of radioactive waste and released some of it into the Columbia river. It is the most contaminated nuclear facility in the United States, and clean up efforts are costing more than \$2 billion per year. By some estimates the total cleanup bill will reach \$120 billion dollars.

4. Goiania incident

In 1987, a little girl sat on the floor of her home playing with a glowing blue powder. It was caesium - 137, a highly radioactive material. Her father, a junkyard owner, had bought the deadly substance from a pair of men who had broken into an abandoned medical building, looking for scrap metal to sell. The junkyard owner's wife, daughter, and two of his employees died after handling the substance. More than 245 other people fell ill after coming into contact with the radioactive isotope.

5. Fukushima

When a Tsunami struck the Fukushima nuclear power plant in March of 2011, some of its cooling systems failed, sending several reactors spiraling out of control. As temperatures within the reactors rose, massive explosions shook the power plant, releasing some radioactive material and damaging the barriers that are meant to contain nuclear material. In a last ditch effort, nuclear power authorities flooded the reactors with seawater, ensuring that the plant will never again be used.

6. Baneberry test

Of the many nuclear weapons tests conducted at Yucca Flat in Nevada, this 1970 explosion was the biggest disaster. Although the warhead was buried 900 feet below ground, it sent a plume of iodine-131-packed gas up into the jet stream. Soon after, radioactive snow was falling in Northern California.

7. Castle Bravo, a Botched Hydrogen Bomb Test

In 1954, some engineers from Los Alamos National Laboratory made a little miscalculation before a nuclear weapons test. Their hydrogen bomb was more than twice as powerful as expected. It created a 15 megaton blast that showered a Japanese fishing boat and several Pacific islands with radioactive fallout.