Chapter One: Radioactivity and radiation

1- Introduction

It is found that a few naturally occurring substances consist of atoms which are unstable that is, they undergo spontaneous transformation into more stable product atoms. Such substances are said to be radioactive, and the transformation process is known as radioactive decay. Radioactive decay is usually accompanied by the emission of radiation in the form of charged particles and gamma (γ) rays.

The fact that some elements are naturally radioactive was first realized by Becquerel in 1896. He observed the blackening of photographic emulsions in the vicinity of a uranium compound. This was subsequently attributed to the effect of radiation being emitted by the uranium. In the following 10 years, the experimental work of Rutherford and Soddy, Pierre and Marie Curie and others established the fact that some types of nuclei are not completely stable. These unstable nuclei decay and emit radiations of three main types, called alpha, beta and gamma radiation.

2- Alpha, Beta and Gamma Radiation

Alpha (α) radiation was shown by Rutherford and Royds to consist of helium nuclei, which themselves consist of two protons and two neutrons. These four particles are bound together so tightly that the α particle behaves in many situations as if it were a fundamental particle. An α particle has a mass of 4 units and carries 2 units of positive charge.

Beta (β) radiation consists of high-speed electrons which originate in the nucleus. These 'nuclear electrons' have identical properties to the atomic electrons, that is they have a mass of 1/1840 u and carry one unit of negative charge. Another type of β radiation was discovered by C. D. Anderson in 1932. This consists of particles of the same mass as the electron but with one unit of positive charge; it is known as positron radiation. Although less important from a radiation protection viewpoint than negative β particles, a knowledge of positrons is necessary in order to understand certain radioactive decay mechanisms. Beta radiation is signified β^- (electrons) or β^+ (positrons). In everyday use, the term β radiation normally refers to the negative type β^-

Gamma (γ) radiation, although somewhat analogous to α or β particles, is electromagnetic in nature and can be described as consisting of 'particles' called 'photons'. However, photons do not have any mass or electrical charge, and instead they consist of packets (or 'quanta') of energy transmitted in the form of a wave motion (wave packets). Other well-known members of this class of radiation are radio waves and visible light. The amount of energy in each quantum is related to the wavelength of the radiation. The energy is inversely proportional to the wavelength, which means that the shorter the wavelength the higher the energy. Mathematically, this is written as $E \propto \frac{1}{\lambda}$, where E is the energy of the quantum or photon of electromagnetic radiation and l is its wavelength. Another class of electromagnetic radiation which is in most respects identical to γ radiation is known as X radiation. The essential difference between the two types of radiation lies in their origin. Whereas g-rays result from changes in the nucleus, X-rays are emitted when atomic electrons undergo a change in orbit.

The wavelength of electromagnetic radiation varies over a very wide range, as illustrated in Table 1.

All electromagnetic radiations travel through free space with the same velocity of $3*10^8$ m/s. Their velocity decreases in dense media, but in air the decrease is negligible.

Table 1 Wavelengths of electromagnetic radiations

Type of radiation	Wavelength, λ (m)
Radio waves (long wave)	1500
Radio waves (very high frequency)	3
Visible light	$10^{-6}-10^{-7}$
X-rays, 50 keV energy	2.5×10^{-11}
γ-rays, 1 MeV energy	1.2×10^{-12}

3- THE ELECTRONVOLT

Radiation energy is expressed in electronvolt (eV). One electronvolt is the energy gained by an electron in passing through an electrical potential of 1 volt. For example, in an X-ray tube, electrons are accelerated from a heated tungsten filament through an electrical potential of typically 100 000 volts to the anode. The electrons therefore have an energy of 100 000 eV when they strike the anode.

The electronvolt is a very small unit, so radiation energies are usually expressed in kilo (1000) or mega (1 000 000) electronvolts:

One kiloelectronvolt = 1 keV = 1000 eV

One megaelectronvolt = 1 MeV = 1000 keV = 1 000 000 eV

The radiation energies of interest in radiation protection are generally in the range of 100 keV to 10 MeV. It is important to appreciate that even if the radiation being considered is not β (electron) radiation, it is still possible to express its energy in terms of the electronvolt. The energy of a particle depends on its mass and velocity; for example, the kinetic energy (EK) of a particle of mass (m) travelling with velocity (v) which is much smaller than the velocity of light is given by the equation:

$$K_E = \frac{1}{2}mv^2$$

(A correction is necessary for particles which have velocities approaching the velocity of light.) A small particle such as an electron requires a much higher velocity than, say, an α particle in order to have the same kinetic energy.

In the case of electromagnetic radiation, the energy is inversely proportional to the wavelength of the radiation. Thus, radiations with short wavelengths have higher energies than radiations with longer wavelengths. Note that all electromagnetic radiation travels at the speed of light.

4- THE MECHANISM OF RADIOACTIVE DECAY

The nuclei of the heavier elements found in nature are so large that they are slightly unstable. For example, the isotope uranium-238 has 92 protons and 146 neutrons. To achieve greater stability, the nucleus may emit a particle, thus reducing its numbers of protons and neutrons to 90 and 144, respectively. This means that the nucleus now has an atomic number (Z) of 90 instead of 92 and so is no longer a uranium nucleus. It is now an isotope of the element thorium (Th), with an atomic number of 90 and a mass number of 234, namely thorium-234 (^{234}Th). This decay process may be represented as follows:

$$^{238}_{92}\mathrm{U} \longrightarrow {}^{4}_{2}\alpha + {}^{234}_{90}\mathrm{Th}$$

Or, more commonly:

$$^{238}_{92}\mathrm{U} \xrightarrow{\alpha} {}^{234}_{90}\mathrm{Th}$$

Another example of this process is the decay of polonium-218 (^{218}Po) by α emission to lead-214 (^{214}Pb):

$$^{218}_{84}\mathrm{Po} \xrightarrow{\alpha} {}^{214}_{82}\mathrm{Pb}$$

It was pointed out in Chapter 1 that there are more neutrons than protons in heavy nuclei. α Emission reduces the number of each by two, but the proportionate reduction is considerably less for neutrons than for protons. In the ^{238}U decay process, the number of protons is reduced by 2 out of 92, whereas the number of neutrons is reduced by 2 out of 146, which is, proportionately, significantly less. The effect of α emission is therefore to produce neutron-rich nuclei that are still unstable. The nucleus does not simply eject a neutron (or neutrons) to correct this instability. Instead, one of the neutrons in the nucleus changes into a proton by emitting a β particle, that is, a high-speed electron:

$$ {}^{1}_{0}n \longrightarrow {}^{1}_{1}p + \beta^- $$

This phenomenon is known as β emission. In the case of ^{234}Th, formed by the α decay of ^{238}U, the nucleus further decays by β emission to protactinium-234 (^{234}Pa):

$$ {}^{234}_{90}Th \longrightarrow {}^{234}_{91}Pa + \beta^- $$

or:

$$ {}^{234}_{90}Th \xrightarrow{\beta^-} {}^{234}_{91}Pa $$

Considering again polonium-218, the complete decay is:

$$ {}^{218}_{84}Po \xrightarrow{\alpha} {}^{214}_{82}Pb \xrightarrow{\beta^-} {}^{214}_{83}Bi $$

The resulting atom is bismuth-214, which is also unstable and so further α- and β-decay processes occur until a stable atom is produced.

Electrons emitted during β decay have a continuous distribution in energy, ranging from zero to a maximum energy (E_{max}), which is characteristic of the particular nucleus.

The most probable β energy is about $\frac{1}{3}E_{max}$ (see Fig. 1).

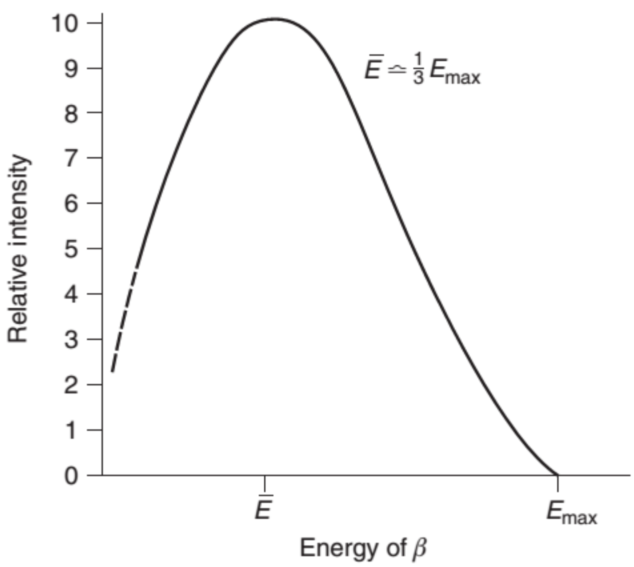

Fig. 1: Typical β spectrum.

In most cases, after the emission of an α or β particle, the nucleus rearranges itself slightly, releasing energy by λ emission.

Two other decay processes should also be mentioned, namely positron emission and electron capture. In positron emission, a proton in the nucleus ejects a positive electron (β^+) and so becomes a neutron:

$$^{1}_{1}p \longrightarrow {}^{1}_{0}n + \beta^{+}$$

For example, sodium-22 (^{22}Na) decays by positron emission to neon-22:

$$^{22}_{11}Na \xrightarrow{\beta^{+}} {}^{22}_{10}Ne$$

Electron capture is a process in which an electron from an inner orbit is captured by the nucleus, resulting in the conversion of a proton to a neutron:

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

A rearrangement of atomic electrons then causes the emission of X-rays.

5- NATURAL RADIOACTIVE SERIES

Apart from ^{22}Na, the above examples of radioactive decay are all naturally occurring radioactive substances and belong to the so-called natural radioactive series. There are three natural radioactive series, called the thorium, uranium–radium and actinium series (see Table 2). Also included in this table is the neptunium series, the longest member of which has a half-life ($T_{½}$) of 2.2 * 10^6 years. This is much less than the age of the Earth and so the series has long since decayed. However, neptunium-237 is produced artificially in nuclear reactors and can be important in some situations.

Series name	Final stable nucleus	Longest-lived member
Thorium	^{208}Pb	^{232}Th ($T_{1/2}$ = 1.39 × 10^{10} years)
Uranium–radium	^{206}Pb	^{238}U ($T_{1/2}$ = 4.50 × 10^{9} years)
Actinium	^{207}Pb	^{235}U ($T_{1/2}$ = 8.52 × 10^{8} years)
Neptunium	^{209}Bi	^{237}Np ($T_{1/2}$ = 2.20 × 10^{6} years)

The term ‘series’ is used because an atom undergoes a succession of radioactive transformations until it reaches a stable state. In the thorium series, the atom is initially thorium-232 and undergoes a series of radioactive decays as follows:

$$^{232}_{90}Th \xrightarrow{\alpha} {}^{228}_{88}Ra \xrightarrow{\beta^{-}} {}^{228}_{89}Ac \xrightarrow{\beta^{-}} {}^{228}_{90}Th \xrightarrow{\alpha} {}^{224}_{88}Ra \xrightarrow{\alpha}$$

$$^{220}_{86}Rn \xrightarrow{\alpha} {}^{216}_{84}Po \xrightarrow{\alpha} {}^{212}_{82}Pb \xrightarrow{\beta^{-}} {}^{212}_{83}Bi \xrightarrow{\beta^{-}} {}^{212}_{84}Po \xrightarrow{\alpha} {}^{208}_{82}Pb$$

The half-lives of these members of the decay series range from 0.15 s for polonium-216 to about 1.4 * 10^{10} years for thorium-232.

6- INDUCED RADIOACTIVITY

Lighter elements may be made radioactive by bombarding them with nuclear particles. One such process involves the bombardment of stable nuclei of an element by neutrons in a nuclear reactor. A neutron may be captured by a nucleus with the emission of a γ photon. This is known as a neutron, gamma(n, γ)) reaction. The resulting atom is usually unstable because of the excess neutron and will eventually decay by β emission.

Thus, if the stable isotope cobalt-59 is bombarded or irradiated with neutrons, atoms of the radioactive isotope cobalt-60 are produced. These atoms will eventually undergo β decay and become atoms of the stable isotope nickel-60. This process is written as:

$$^{59}_{27}\mathrm{Co}(\mathrm{n},\gamma)^{60}_{27}\mathrm{Co} \xrightarrow{\beta^-} {}^{60}_{28}\mathrm{Ni}$$

There are various other activation and decay processes, which will be discussed later.

7- THE UNIT OF RADIOACTIVITY

The decay of a radioactive sample is statistical in nature and it is impossible to predict when any particular atom will disintegrate. The consequence of this random behaviour of radioactive atoms is that the radioactive decay law is exponential in nature, and is expressed mathematically as:

$$N_t = N_0 e^{-\lambda t}$$

Where N_0 is the number of nuclei present initially, $N_t$is the number of nuclei present at time t and λ is the radioactive decay constant. The half-life ($T_{½}$) of a radioactive species is the time required for one-half of the nuclei in a sample to decay. It is obtained by putting $N_t = \frac{N_0}{2}$ in the above equation:

$$N_0/2 = N_0 e^{-\lambda T½}$$

Dividing across by N_0 and taking logs:

$$\log_e(½) = -\lambda T_{½}$$

Now:

$$\log_e(½) = -\log_e(2)$$

And so:

$$T_{½} = \frac{\log_e 2}{\lambda} = \frac{0.693}{\lambda}$$

Since the disintegration rate, or activity, of the sample is proportional to the number of unstable nuclei, this also varies exponentially with time in accordance with the equation:

$$A_t = A_0 e^{-\lambda t}$$

This relationship is illustrated in Figure 2, which shows the variation of sample activity with time. In one half-life the activity decays to $½A_0$, in two half-lives to $¼A_0$, and so on. In practice, the decay of a sample is usually plotted on a log-linear graph in which the vertical axis has a logarithmic scale. The plot then becomes a straight line with a slope that depends on the half-life of the sample. The half-life of a particular radioactive isotope is constant and its measurement assists in the identification of radioactive samples of unknown composition.

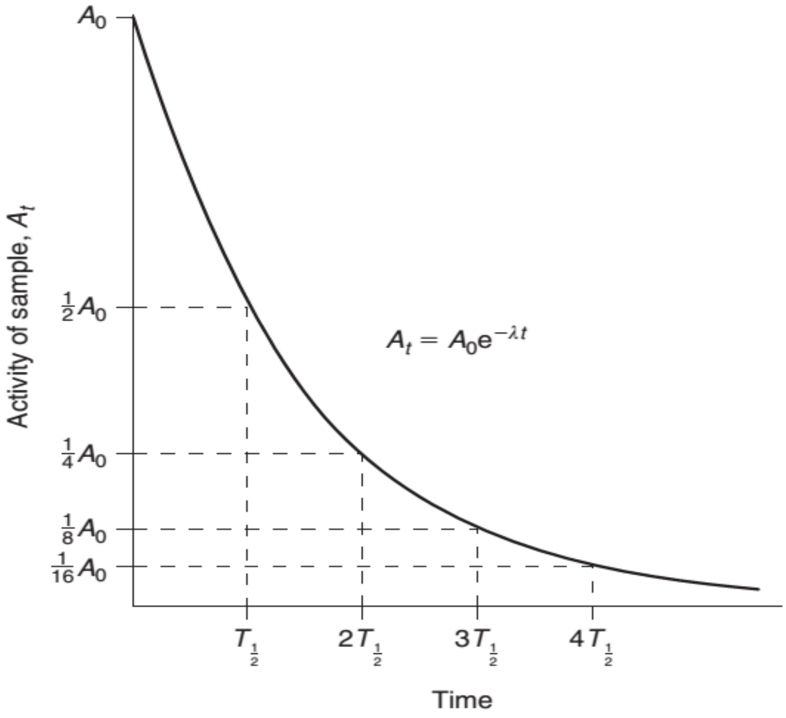

Figure 2: Variation of activity with time.

This method can be applied only to isotopes whose disintegration rates change appreciably over reasonable counting periods. At the other end of the scale, the isotope must have a long enough half-life to allow some measurements to be made before it all disintegrates. To determine extremely short and extremely long half-lives, more elaborate means must be used. Half-lives range from about 10^{-14} years (^{212}Po) to about 10^{17} years (^{209}Bi), which represents a factor of 10^{31}.

For many years, the unit of radioactivity was the curie (C_i), but this has now been generally replaced by the SI (Système International d'Unités) unit, the Becquerel (Bq).

The curie was originally related to the activity of 1 g of radium, but the definition was later standardized as 3.7 *10^{10} nuclear disintegrations (dis)/s, which is almost the same:

1 C_i = 3.7 * 10^{10} dis/s or 2.22 * 10^{12} dis/min

The Becquerel is defined as one nuclear disintegration per second and, compared with the curie, it is a very small unit. In practice, most radioactive sources are much larger than the Becquerel and the following multiplying prefixes are used to describe them:

1becquerel (Bq) = 1 dis/s

1kilobecquerel (kBq) = 10^3 Bq = 10^3 dis/s

1megabecquerel (MBq) = 10^6 Bq = 10^6 dis/s

1gigabecquerel (GBq) = 10^9 Bq = 10^9dis/s

1terabecquerel (TBq) = 10^{12} Bq = 10^{12}dis/s

1petabecquerel (PBq) = 10^{15} Bq = 10^{15} dis/s

For simplicity, in this text only Bq, MBq and TBq have been used.

As explained earlier, a disintegration usually involves the emission of a charged particle (α or β). This may be accompanied, although not always, by one or more γ emissions.

Some nuclides emit only x or γ radiation.

8- THE NUCLIDE CHART

The nuclide chart is a compilation of information on all known stable and unstable nuclides and a portion of it is reproduced in Figure 3.

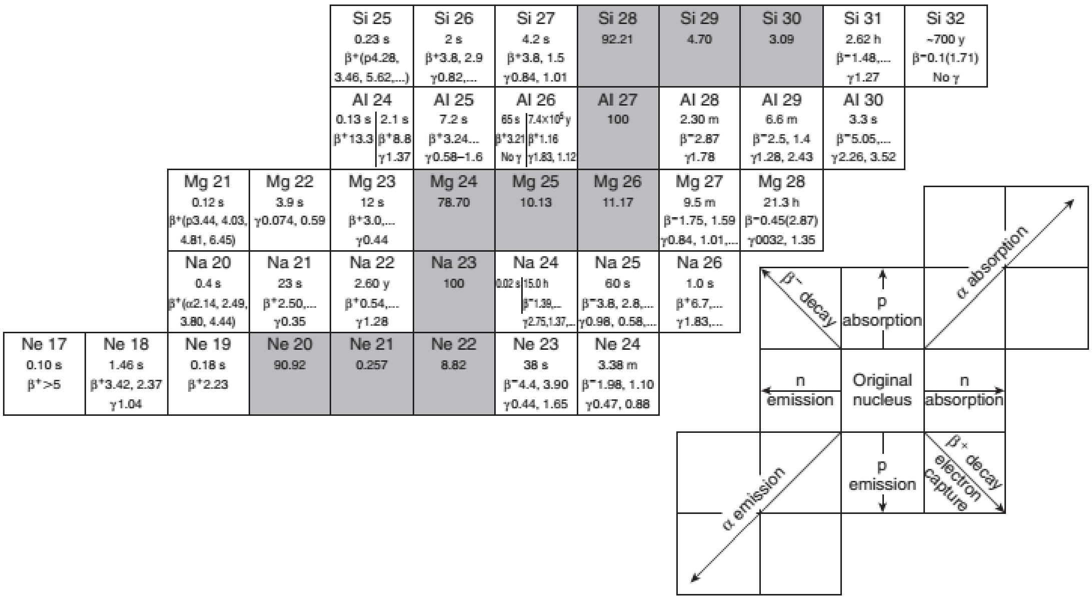

Figure 3: A portion of the nuclide chart.

In the chart, each horizontal line represents an element and the squares on that line represent the nuclides or isotopes of the element. Relevant information regarding the nuclide is printed inside the square. Stable, naturally radioactive and artificial nuclides are differentiated by the use of different colours or shading of the squares. In each case the symbol and mass number are shown as well as the natural abundance of the isotope.

For radioactive isotopes, the half-life, the mode or modes of decay, and the main energies of the emitted particles or γ rays are shown. In the chart illustrated in Figure 3, all the nuclides on the same horizontal line have the same atomic number, while all nuclides with the same mass number lie on a 45° diagonal line running from the upper left to the lower right. Many nuclide charts contain additional information which has been omitted from the sample chart shown in Figure 3 for the sake of clarity.

Also shown at the lower right of the figure is the effect on the original nucleus of various capture or decay reactions. For example, an n, γ reaction on a nucleus moves it one space to the right on the same row. Thus, an n, γ reaction on sodium-23 (^{23}Na) produces sodium-24 (^{24}Na). This ^{24}Na decays with a half-life of 15.0 h by emitting β^{-}particles of 1.39 MeV and γ rays of 2.75 MeV and 1.37 MeV. The nucleus resulting from the decay of ^{24}Na is magnesium-24 (^{24}Mg), which is stable.

9- INTERACTION OF RADIATION WITH MATTER

9-1: Charged particles

Both α and β particles lose energy mainly through interactions with atomic electrons in the absorbing medium. The energy transferred to the electrons causes them either to be excited to a higher energy level (excitation) or separated entirely from the parent atom (ionization). Another important effect is that when charged particles are slowed down very rapidly, they emit energy in the form of X-rays. This is known as bremsstrahlung (braking radiation) and is of practical importance only in the case of β radiation.

9-2: X and γ radiations

X and γ radiations interact with matter through a variety of alternative mechanisms, the three most important of which are the photoelectric effect, Compton scattering and pair production. In the photoelectric effect, all the energy of a X- or γ photon is transferred to an atomic electron which is ejected from its parent atom. The photon is, in this case، completely absorbed. Conversely, when Compton scattering occurs, only part of the energy of the photon is transferred to an atomic electron. The scattered photon then continues with reduced energy.

In the intense electric field close to a charged particle, usually a nucleus, an energetic γ photon may be converted into a positron–electron pair. This is pair production, and the two resulting particles share the available energy.

Thus, all three interactions result in the photon energy being transferred to atomic electrons which subsequently lose energy, as described in section 9.1.

Neutrons are uncharged and cannot cause ionization directly. Neutrons ultimately transfer their energy to charged particles. Also a neutron may be captured by a nucleus, usually resulting in γ emission. Table summarizes the types of interactions of nuclear radiations with matter.

Radiation	Process	Remarks
α	Collisions with atomic electrons	Leads to excitation and ionization
β	(a) Collisions with atomic electrons	Leads to excitation and ionization
	(b) Slowing-down in field of nucleus	Leads to emission of bremsstrahlung
X and γ radiation	(a) Photoelectric effect (b) Compton effect (c) Pair production	Photon is completely absorbed Only part of the photon energy is absorbed
Neutron	(a) Elastic scattering (b) Inelastic scattering (c) Capture processes	Discussed in Chapter 8

10- PENETRATING POWERS OF NUCLEAR RADIATIONS

The α particle is a massive particle (by nuclear standards) that travels relatively slowly through matter. It thus has a high probability of interacting with atoms along its path and will give up some of its energy during each of these interactions. As a consequence, α particles lose their energy very rapidly and travel only very short distances in dense media. Beta particles are very much smaller than α particles and travel much faster. They thus undergo fewer interactions per unit length of track and give up their energy more slowly than α particles. This means that β particles travel further in dense media than α particles.

Gamma radiation loses its energy mainly by interacting with atomic electrons. It travels very large distances even in dense media and is very difficult to absorb completely.

Neutrons give up their energy through a variety of interactions, the relative importances of which are dependent on the neutron energy. For this reason, it is common practice to divide neutrons into at least three energy groups: fast, intermediate and thermal. Neutrons are very penetrating and will travel large distances even in dense media.

The properties and ranges of the various nuclear radiations are summarized in Table 4. The ranges are only approximate since they depend on the energy of the radiation.

Table 4: Properties of nuclear radiations.

Radiation	Mass (u)	Charge	Range in air	Range in tissue
α	4	+2	~0.03 m	~0.04 mm
β	1/1840	-1 (positron +1)	~3 m	~5 mm
X and γ radiation	0	0	Very large	Through body
Fast neutron	1	0	Very large	Through body
Thermal neutron	1	0	Very large	~0.15 m

SUMMARY OF KEY POINTS

Radioactive decay: transformation of an unstable atomic nucleus into a more stable one، usually accompanied by the emission of charged particles and γ-rays.

Alpha (α) radiation: helium nuclei, two protons and two neutrons, mass 4 units, charge +2 units.

Beta (β) radiation: high-speed electrons which originate in the nucleus, mass 1/1840 u, charge −1 (electron) or +1 (positron).

Gamma (γ) radiation: electromagnetic radiation, very short wavelength, $E \propto \frac{1}{\lambda}$, mass 0, charge 0.

Electronvolt: energy gained by an electron in passing through an electric potential of 1 volt.

10^6eV ≡ 10^3 keV ≡ 1 MeV

Natural radioactive series consist of naturally occurring radioactive substances; the three series are thorium, uranium–radium and actinium.

Induced radioactivity: radioactivity caused by bombarding stable atoms with nuclear particles, for example by neutrons in a nuclear reactor.

Radioactive decay law:

$$N_t = N_0 e^{-\lambda t}$$

Half-life: time required for one half of the nuclei of a radioactive species to decay:

$$T_{½} = \frac{0.693}{\gamma}$$

Curie (Ci): former unit of radioactivity defined as 3.7 * 10^{10}dis/s.

1Ci ≡ 10^3 mCi ≡ 10^6 μCi

Becquerel (Bq): SI unit of radioactivity, defined as 1 dis/s.

1TBq ≡ 10^6 MBq ≡ 10^{12} Bq

Nuclide chart: compilation of data on all known nuclides.

Alpha particles lose energy in matter through excitation and ionization.

Beta particles lose energy by:

1- Excitation and ionization of atomic electrons, and

2- Rapid slowing down with emission of bremsstrahlung.

Gamma photons lose energy through:

1- Photoelectric effect،

2- Compton effects, and

3- pair-production.

Neutrons lose energy through:
1- Elastic scatter،
2- Inelastic scatter, and
3- Capture reactions.

REVISION QUESTIONS

1. Explain the difference between radioactivity and radiation.
2. Using a nuclide chart, name the products of the following radioactive decay processes:
(a) α decay of uranium-238, $^{238}_{92}U$,
(b) β^- decay of tritium, $^{3}_{1}H$,
(c) β^+ decay of copper-62, $^{62}_{29}Cu$.
3. Explain why the radionuclides of the neptunium decay series are not found in nature.
4. Estimate the half-life of a radioactive sample by plotting a graph of the following series of measurements:

Time (min)	0	1	2	3	4	5	6	7	8
Activity (counts/min)	–	820	605	447	330	243	180	133	98

5. Express the following activities in megabecquerels:
(a) $5 * 10^6$ dis/s،
(b) 750 kBq،
(c) 1.3 GBq،
(d) $6 * 10^7$ dis/min.
6. Why is an α decay usually followed by a β^- decay؟
7. Using a nuclide chart, write down the product or sequence of products which would result from an (n, γ) capture in the following nuclei:
(a) $^{58}_{27}Fe$,
(b) $^{23}_{11}Na$,
(c) $^{239}_{94}Pu$.