South Valley University

Faculty of Science, Qena

Physics Department

Radiation physics

الفيزياء الاشعاعية

الفرقة الرابعة كلية التربية

تعليم اساسي شعبة العلوم لغات

اعداد

د/ عادل جادالكريم عبادي محمد

أستاذ الفيزياء الإشعاعية والنووية المساعد

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Content

CHAPTER 1
The structure of matter

1.1 INTRODUCTION

Matter is the name given to the materials of which the universe is composed. It exists in three physical forms: solid, liquid or gas. All matter consists of a number of simple substances called elements.

An **element** is a substance that cannot be broken down by ordinary chemical processes into simpler substances. There are 92 naturally occurring elements, some examples of which are carbon, oxygen, iron and lead. Another 25 or so have been produced artificially over the past 75 years, the best known of which is plutonium.

In nature, elements are usually chemically linked to other elements in the form of compounds. A **compound** consists of two or more elements chemically linked in definite proportions, for example water, H_2O, which consists of two atoms of hydrogen and one atom of oxygen.

1.2 THE ATOM

Consider an imaginary experiment in which a quantity of some element is subjected to repeated subdivisions. Using ordinary optical instruments, a stage would eventually be reached when the fragments would cease to be visible. Supposing, however, that suitable tools and viewing apparatus were available, would it be possible to repeat the divisions of the original element indefinitely, or would a stage be reached where the matter can no longer be subdivided?

More than 2000 years ago, Greek philosophers considered this question. With none of our modern instruments available to them, all they could do was consider the problem in a logical manner. From this philosophical approach, some of them decided that eventually a limit must be reached. They called the individual particles of matter which could not be further subdivided **atoms**. It was also postulated by some of the philosophers that all substances consist of these same atoms, different arrangements of the constituent atoms giving the different properties of the substances and the density being determined by how tightly the atoms are packed.

Early in the nineteenth century, an atomic theory with a scientific basis was advanced which confirmed many of the views held by the ancient philosophers. This was the atomic theory of Dalton, which was able to explain the well-established but little-understood chemical laws. Modern theory has diverged somewhat from Dalton's but he did establish the principle that matter consists of atoms, each element having its own characteristic atom.

1.3 THE STRUCTURE OF THE ATOM

It is now known that atoms are not solid, indivisible objects as the Greek philosophers believed but are composed of even smaller particles. These particles, from which all atoms are constructed, are called **protons**, **neutrons** and **electrons**.

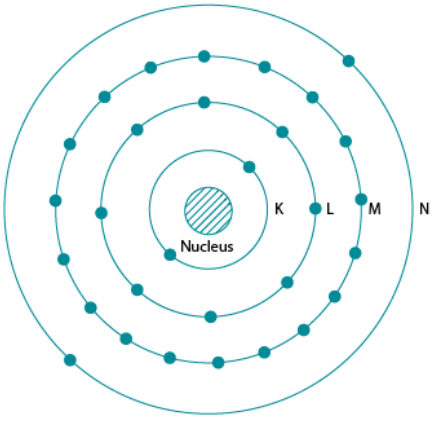


Figure 1.1 The atomic system of zinc.

The **proton** (p) carries a positive electrical charge of magnitude 1 unit on the nuclear scale, and a mass of approximately 1 atomic mass unit (u).

The **electron** (e−) has a negative electrical charge of the same magnitude as the proton's positive charge. It has a mass of 1/1840 u, which, for most purposes, is neglected when considering the mass of the atom.

The **neutron** (n) is electrically neutral and has a mass of approximately 1 u. It can be helpful in understanding the processes of radioactive decay (see Chapter 2) to regard the neutron as a close combination of a proton and an electron, with the positive charge of the proton being cancelled by the negative charge of the electron.

It should be realized that the charges and masses on the nuclear scale are extremely small. The electrical charge associated with a proton or electron is about 1.6×10^{-19} coulombs (C). For comparison, the charge stored in a typical A A-type battery is about 5000 C. Similarly, 1 u corresponds to a mass of about 1.7×10^{-27} kg.

The neutrons and protons of an atom form a central core or nucleus, around which the electrons occupy various orbits, normally referred to as shells. The shell closest to the nucleus can contain a maximum of two electrons, the second can have up to eight, and the outer shells have progressively greater numbers. The inner shell is known as the **K shell**, the second is called the **L shell**, the third the **M shell**, the fourth the **N shell** and so on. The maximum numbers of electrons in the K, L, M and N shells are 2, 8, 18 and 32, respectively. For example, the atomic system of zinc, illustrated in Figure 1.1, has 30 electrons arranged in four shells.
Each atom normally has the same number of protons as electrons. This means that the total positive charge on the nucleus is equal to the total negative charge of the atomic electrons, and so the atom is normally electrically neutral. Two simple atoms, those of hydrogen and helium, are illustrated in Figure 1.2. This particular hydrogen atom is the only atom that does not contain neutrons. This is because the repulsive positive charges do not allow more than one proton to form a nucleus without the presence of one or more neutrons.

1.4 ELEMENTS AND ATOMIC NUMBER

In the early stages of the evolution of the universe, the two elements hydrogen and helium constituted essentially 100% of matter (apart from a very small

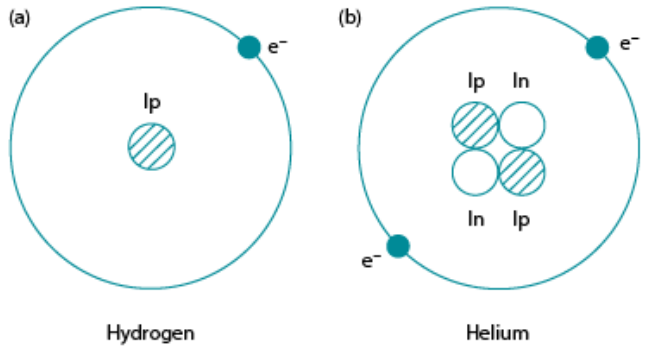


Figure 1.2 The atomic systems of hydrogen and helium.

quantity of lithium). However, processes occurring during the life cycles of early generations of stars resulted in the production of heavier elements by successive fusion reactions. This process, known as nucleosynthesis, eventually led to the creation of all the elements that are found on Earth today.
Each element is characterized by the number of protons in the atomic nucleus and this is called the atomic number, represented by the symbol *Z*:

Atomic number (Z) = Number of protons

For example, hydrogen has one proton, $Z = 1$, and helium has two protons, $Z = 2$. It is the number of electrons in an atom that determines its chemical properties. In an electrically neutral atom, the number of protons equals the number of electrons, and so, indirectly, it is the number of protons in an atom that defines the element. Table 1.1 lists a selection of elements with their symbols and atomic numbers.

About 25 elements of a higher atomic number have been artificially produced in small quantities over the past 75 years or so. They are all unstable and can only be created by processes that do not occur naturally on Earth.

1.5 ISOTOPES AND MASS NUMBER

Although all the atoms of a particular element contain the same number of protons, they may occur with different numbers of neutrons. This means that an element can have several types of atoms. For example, hydrogen can occur with zero, one or two neutrons in its nucleus, and the three different types of atoms are called **isotopes** of hydrogen.

The mass of an atom is determined by the number of protons and neutrons if the very small mass of the atomic electrons is neglected. The sum of the number of protons plus the number of neutrons is

Table 1.1 Selection of elements with symbols and atomic numbers

Element	Symbol	Atomic number Z	Element	Symbol	Atomic number Z
Hydrogen	H	1	Oxygen	O	8
Helium	He	2	Aluminium	Al	13
Lithium	Li	3	Iron	Fe	26
Beryllium	Be	4	Silver	Ag	47
Boron	B	5	Lead	Pb	82
Carbon	C	6	Uranium	U	92

called the **mass number** and is represented by the symbol A:

Mass number (A) = Number of protons + Number of neutrons

For example, the helium atom in Figure 1.2b contains two protons and two neutrons and so has a mass number of 4. Helium can also occur with one or three neutrons in the nucleus, as shown in Figure 1.3. These three isotopes are normally referred to as helium-3, helium-4 and helium-5, usually written as He-3, He-4 and He-5.

An isotope can also be written in symbolic form as ${}_{Z}X^{A}$, where X is the symbol for the element. In this format, helium-3 is written ${}_{2}^{3}He$. Strictly, showing the atomic number is unnecessary because the name of the element defines the atomic number, so in most cases it is sufficient to write this as 3He. Throughout this text, the notation X-A is used (e.g. He-3) except where inclusion of the atomic number assists an understanding of the topic or where it is felt necessary to give the full name of the element.

Considering another example, the element phosphorus (P) has an atomic number of 15 (i.e. each atom contains 15 protons) and it occurs in its stable, natural form as P-31, which means that the nucleus contains 16 neutrons. However, other isotopes can be produced by artificial means, though these are all unstable. They include isotopes between P-28 and P-34, as listed next:

P-28 has 15 protons and 13 neutrons ($Z = 15$, $A = 28$)
P-29 has 15 protons and 14 neutrons ($Z = 15$, $A = 29$)
P-30 has 15 protons and 15 neutrons ($Z = 15$, $A = 30$)
P-31 has 15 protons and 16 neutrons ($Z = 15$, $A = 31$)
P-32 has 15 protons and 17 neutrons ($Z = 15$, $A = 32$)
P-33 has 15 protons and 18 neutrons ($Z = 15$, $A = 33$)
P-34 has 15 protons and 19 neutrons ($Z = 15$, $A = 34$)

It is important to note that all the isotopes of a given element are **chemically** identical since the chemical properties are determined by the atomic number of the element.

Most elements occur naturally as a mixture of isotopes, and other isotopes may be produced by bombarding a naturally occurring isotope with nuclear particles, for example by neutrons in a nuclear reac-

tor. These artificially produced isotopes are unstable and will eventually disintegrate with the emission of a secondary particle (see Chapter 2).
Apart from the few lightest elements, the number of neutrons exceeds the number of protons in an atom. The difference becomes greater as the atomic number increases, as illustrated by the following examples:
He-4 has 2 protons and 2 neutrons
P-31 has 15 protons and 16 neutrons
Zn-65 has 30 protons and 35 neutrons
U-238 has 92 protons and 146 neutrons
Data on the known isotopes of all the elements, both naturally occurring and artificially produced, have been arranged systematically in a table known as the **chart of the nuclides**, which will be discussed in more detail in Chapter 2. The term **nuclide** means any isotope of any element.

ANCIENT AND MODERN THEORIES

It can now be seen that the ancient Greek philosophers were remarkably close to the truth in their theory that all substances are constituted from the same basic particles. However, instead of being different arrangements of only one type of particle, different substances appear to result from various combinations of protons, neutrons and electrons. It is now known that protons and neutrons are made up of even smaller particles called quarks, and there is some evidence of apparently more fundamental particles. Thus, the ancient Greeks may yet prove to have been right in their conjecture that there is just one fundamental particle that provides the basis for all others.

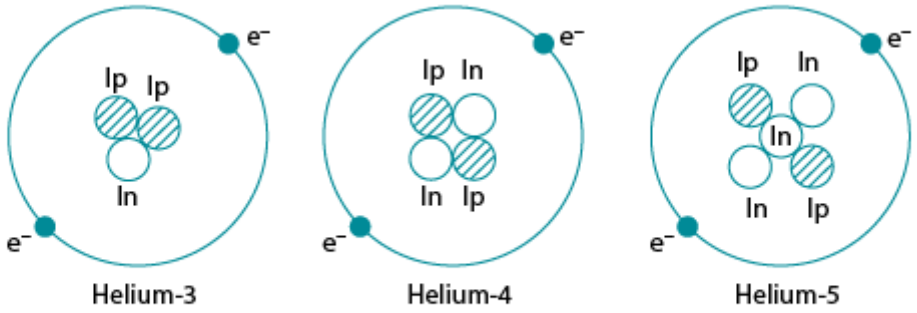


Figure 1.3 The three isotopes of helium.

1.6 Properties and structure of matter

Matter has several fundamental properties. For our purposes, the most important are mass and charge (electric). We recognize mass by the force gravity exerts on a material object (commonly referred to as its weight) and by the object's inertia, which is the "resistance" we encounter when we attempt to change the position or motion of a material object. Similarly, we can, at least at times, recognize charge by the direct effect it can have on us or that we can observe it to have on inanimate objects. For example, we may feel the presence of a strongly charged object when it causes our hair to move or even to stand on end. More often than not, however, we are insensitive to charge. But whether grossly detectable or not, its effects must be considered here because of the role charge plays in the structure of matter.
Charge is generally thought to have been recognized first by the ancient Greeks. They noticed that some kinds of matter, an amber rod for example, can be given an electric charge by rubbing it with a piece of cloth. Their experiments convinced them that there

are two kinds of charge: opposite charges, which attract each other, and like charges, which repel. One kind of charge came to be called positive, and the other negative. We now know that negative charge is associated with electrons.

Matter is composed of molecules. In any chemically pure material, the molecules are the smallest units that retain the characteristics of the material itself. For example, if a block of salt were to be broken into successively smaller pieces, the smallest fragment with the properties of salt would be a single salt molecule (Figure 1.2). With further fragmentation, the molecule would no longer be salt.
Molecules, in turn, are composed of atoms. Most molecules consist of more than one kind of atom salt, for example, is made up of atoms of chlorine and atoms of sodium. The atoms themselves are composed of smaller particles, the subatomic particles, which are discussed later. The molecule is held together by chemical bonds among its atoms. These bonds are formed by the force of electrical attraction between oppositely charged parts of the molecule.

This force is often referred to as the Coulomb force after Charles A. de Coulomb, the physicist who characterized it. This is the force involved in chemical reactions such as the combining of hydrogen and oxygen to form water. The electrons of the atom are held by the electrical force between them and the positive nucleus. The nucleus of the atom is held together by another type of force—the nuclear force—which is involved in the release of atomic energy. Nuclear forces are orders of magnitude greater than electrical forces.

Elements

There are more than 100 species of atoms. These species are referred to as elements. Most of the known elements—for example, mercury, helium, gold, hydrogen, and oxygen—occur naturally on earth; others are not usually found in nature but are made by humans—for example, europium and americium. A reasonable explanation for the absence of some elements from nature is that if and when they were formed, they proved too unstable to survive in detectable amounts into the present.
All the elements have been assigned symbols or abbreviated chemical names, for example gold, Au;mercury, Hg; and helium, He. Some symbols are obvious abbreviations of the English name; others

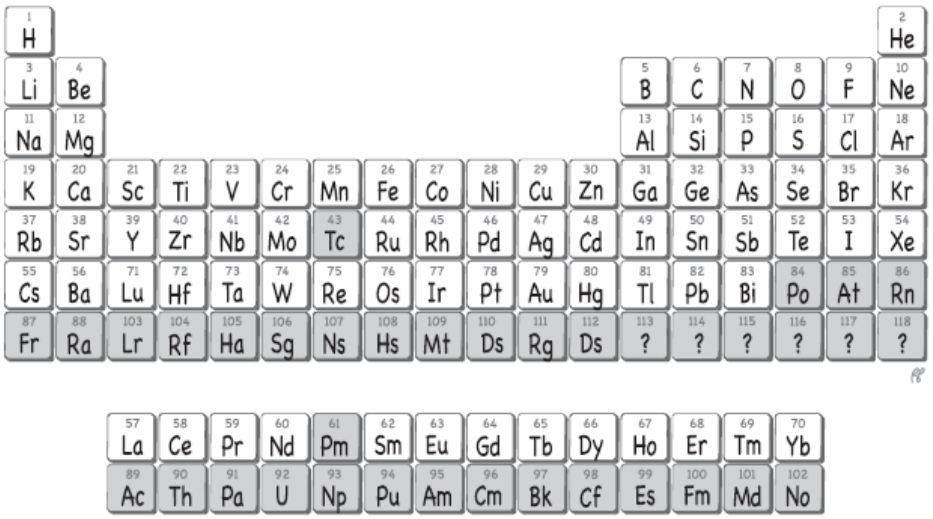


Figure 1.3 Periodic table.

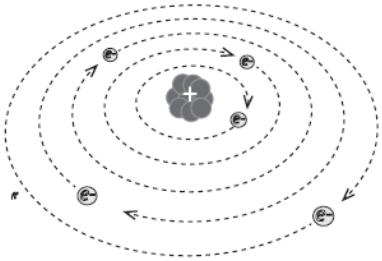


Figure 1.4 Flat atom. The standard two-dimensional drawing of atomic structure.

are derived from the original Latin name of the element. For example, Au is from aurum, the Latin word for gold. All of the known elements, both natural and those made by humans, can be organized into the periodic table. In Figure 1.3, the elements that have a stable state are shown in white boxes; those that occur only in a radioactive form are shown in gray boxes. The number appearing above each element's abbreviation is referred to as the atomic number, which will be discussed later in this chapter.

The elements in the periodic table are arranged in columns (called groups) and rows (called periods). In general, elements within groups demonstrate similar properties. This is because elements in a group often have similar numbers of electrons in their outer shell; outer-shell electron configurations are more important in determining how an atom interacts with other elemental atoms. The lanthanides and actinides are special groups of elements,

conventionally shown in rows separated from and placed below the table. These two groups have the same number of outer-shell electrons and share many common properties.

Atomic structure

Atoms initially were thought of as no more than small pieces of matter. Our understanding that they have an inner structure has its roots in the observations of earlier physicists that the atoms of which matter is composed contain **electrons** of negative charge. Inasmuch as the atom as a whole is electrically neutral, it seemed obvious that it must also contain something with a positive charge to balance the negative charge of the electrons. Thus, early

attempts to picture the atom, modeled on our solar system, showed the negatively charged electrons orbiting a central group of particles, the positively charged **nucleus** (Figure 1.4).

Electrons

In our simple solar-system model of the atom, the electrons are viewed as orbiting the nucleus at high speeds. They have a negative charge and the nucleus has a positive charge. The electrical charges of the atom are "balanced," that is, the total negative charge of the electrons equals the positive charge of

the nucleus. As we shall see in a moment, this is simply another way to point out that the number of orbital electrons equals the number of nuclear protons.

Electron shells: By adding a third dimension to our model of the atom, we can depict the electron orbits as the surfaces of spheres (called **shells**) to suggest that, unlike the planets orbiting the Sun, electrons are not confined to a circular orbit lying in a single plane but may be more widely distributed (Figure 1.5). Although it is convenient for us to talk about the distances and diameters of the shells, distance on the atomic scale does not have quite the same meaning as it does with everyday objects. The more significant characteristic of a shell is the energy
that it signifies. The "closer" an electron is to the nucleus, the more tightly it is bound to the nucleus.
In saying this, we mean that more work (energy) is required to remove an inner-shell electron than an outer one. The energy that must be put into the atom to separate an electron is called the **electron binding energy**. It is usually expressed in **electron volts** (eV). The electron binding energy varies from a few thousand electron volts (keV) for innershell electrons to just a few eV for the less tightly bound outer-shell electrons.

Electron volt

The electron volt is a special unit defined as the energy required to move one electron against a potential difference of one volt. Conversely, it is also the amount of kinetic (motion) energy an electron acquires if it "falls" through a potential difference of one volt. It is a very small unit on the everyday scale, at only $1.6 \times 10{-}19$ joules (J), but a very convenient unit on the atomic scale. The joule is the Système International (SI) unit of work or energy. For comparison, 1 J equals 0.24 small calories (as opposed to the large calorie (kcal) used to measure food intake).

Stable electron configuration: Just as it takes energy to remove an electron from its atom, it takes energy to move an electron from an inner shell to an outer shell, which can also be thought of as the energy required to pull a negative electron away from the positively charged nucleus. Any vacancy in an inner shell creates an unstable condition, often referred to as an **excited state**.

The electrical charges of the atom are balanced, that is, the total negative charge of the electrons equals the total positive charge of the nucleus. This is simply another way of pointing out that the number of orbital electrons quals the number of nuclear protons. Furthermore, the electrons must fill the shells with the highest binding energy first. At least in the elements of low-atomic-number electrons, the inner shells have the highest binding energy.

If the arrangement of the electrons in the shells is not in the stable state, they will undergo rearrangement in order to become stable, a process often referred to as **de-excitation**. Because the stable configuration of the shells always has less energy than any unstable configuration, the deexcitation releases energy as photons, often as **X-rays**.

Nucleus

Like the atom itself, the atomic nucleus also has an inner structure (Figure 1.8). Experiments have shown that the nucleus consists of two types of particles: **protons**, which carry a positive charge, and **neutrons**, which carry no charge. The general term for protons and neutrons is **nucleons**. The nucleons, as shown in the first two rows of Table 1.1, have a much greater mass than electrons. Like

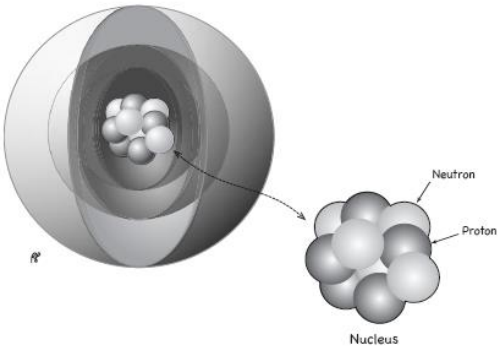
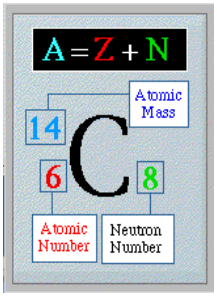


Figure 1.8 The nucleus of an atom is composed of protons and neutrons.

Nuclear Binding Energy

According to the classical electrostatic theory, the nucleus of an atom cannot exist as a single entity, because of the electrostatic repulsive force among the protons in the nucleus. The stability of the nucleus is explained by the existence of a strong binding force called the *nuclear force*, which overcomes the repulsive force of the protons. The nuclear force is effective equally among all nucleons and exists only in the nucleus, having no influ- ence outside the nucleus. The short range of the nuclear force leads to a very small size (~10^{-13} cm) and very high density (~10^{14} g/cm^3) of the nucleus.

The mass M of a nucleus is always less than the combined masses of the nucleons A in the nucleus. The difference in mass ($M - A$) is termed the *mass defect*, which has been used as binding energy for all nucleons in the nucleus. The average binding energy of a nucleon is equal to the total binding energy (calculated from the mass defect) divided by the number of nucleons. It is of the order of 6–9 MeV, although the binding energy of an individual nucleon has a definite value, depending on the shell it occupies. The binding energy of a nucleon must be supplied to completely remove it from the nucleus. Note that whereas the binding energy of the nucleons is in the megaelectron volt (MeV) range, the electron binding energy in the atomic orbital is of the order of kiloelectron volts (keV), a factor of 1000 lower.,…



- Nuclear species == nuclide
  - A nucleons (mass number),
  - Z protons (atomic number)
  - N neutrons (neutron number)
  - A = Z+N
- Nuclides with the same Z == isotopes
- Nuclides with the same N == isotones
- Nuclides with the same A == isobars
- Identical nuclides with different energy states == isomers
  - Metastable excited state ($T_{1/2}$>10^{-9}s)

Table 1.1 The subatomic particles

Name	*Symbol*	*Location*	*Mass*[a]	*Charge*
Neutron	n	Nucleus	1839	None
Proton	p	Nucleus	1836	Positive (+)
Electron	e^-	Shell	1	Negative (−)

[a]Relative to an electron.

electrons, nucleons have quantum properties, including spin. The nucleus has a spin value equal to the sum of the nucleon spin values.

A simple but useful model of the nucleus is a tightly bound cluster of protons and neutrons. Protons naturally repel each other, since they are positively charged; however, there is a powerful binding force called the **nuclear force** that holds the nucleons together very tightly (Figure 1.9). The work (energy) required to overcome the nuclear force, the work to remove a nucleon from the nucleus, is called the **nuclear binding energy**. Typical binding energies are in the range of 6 million to 9 million electron volts (MeV) (approximately one thousand to one million times the electron binding force). The magnitude of the binding energy is related to another fact of nature: the measured mass of a nucleus is always less than the mass expected from the sum of the masses of its neutrons and protons. The "missing" mass is called the **mass defect**, the energy equivalent of which is

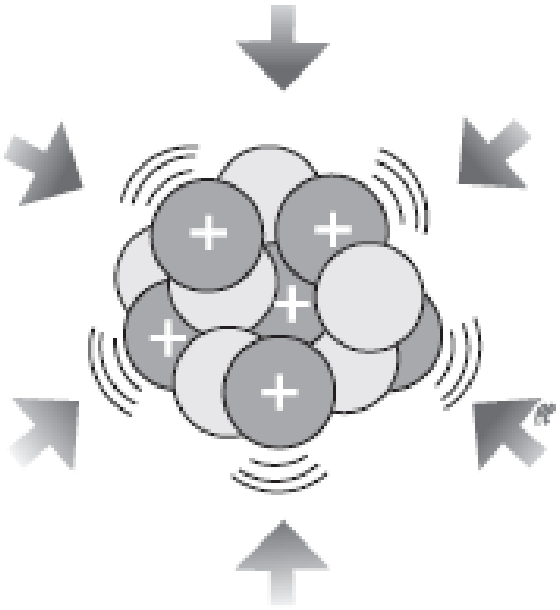


Figure 1.9 The nuclear binding force is strong enough to overcome the electrical repulsion between the positively charged protons.

equal to the nuclear binding energy. This interchangeability of mass and energy was immortalized in Einstein's equation $E = mc^2$.

The stable nucleus: Not all elements have stable nuclei; however, they do exist for most of the light and mid-weight elements, i.e., those with **atomic numbers** (number of protons) up to and including bismuth ($Z = 83$). The exceptions are technetium

(Z = 43) and promethium (Z = 61). All those with atomic numbers higher than 83, such as radium (Z = 88) and uranium (Z = 92), are inherently unstable because of their large size.

For those nuclei with a stable state, there is an optimal ratio of neutrons to protons. For the lighter elements, this ratio is approximately 1 : 1; for increasing atomic weights, the number of neutrons exceeds the number of protons. A plot depicting the number of neutrons as a function of the number of protons is called the **line of stability** (Figure 1.10).

Stability

Strictly speaking, stability is a relative term. We call a nuclide stable when its half-life is so long as to be practically immeasurable—say, greater than 10^8 years. The isotope of potassium ^{40}K, for example, which makes up about 1% of the potassium found in nature, is considered stable but actually has a half-life of 10^9 years.

Isotopes, isotones, and isobars: Each atom of any sample of an element has the same number of protons (the same Z, i.e., atomic number) in its nucleus. Lead found anywhere in the world will always be composed of atoms with 82 protons. The same does not apply, however, to the number of neutrons in the nucleus.

An **isotope** of an element is a particular variation of the nuclear composition of the atoms of that element. The number of protons (Z) is unchanged, but the number of neutrons (*N*) varies. Since the number of neutrons changes, the total number of neutrons and protons (*A*, the atomic mass) changes. The chemical symbol for each element can be expanded to include these three numbers (Figure 1.11).

Two related entities are **isotones** and **isobars**. Isotones are atoms of different elements that contain identical numbers of neutrons but varying numbers of protons. Isobars are atoms of different elements with identical numbers of nucleons. Examples of these are illustrated in Figure 1.12.

SUMMARY OF KEY POINTS

Element: Material whose atoms all have the same number of protons.
u: Atomic mass unit.
Proton: Atomic particle, mass 1 u, charge +1 unit.
Electron: Atomic particle, mass 1/1840 u, charge −1 unit.
Neutron: Close combination of proton and electron, mass 1 u, electrically neutral.
Atom: Central nucleus of protons and neutrons, around which electrons occupy orbits.
Atomic number (*Z*): Number of protons.
Mass number (*A*): Number of protons plus number of neutrons.
Isotope: One of several nuclides with the same atomic number.
Notation: There are several ways of referring to an isotope, for example phosphorus-
32, P-32, 32P and ^{32}P. The convention P-32 is used in this text except where
including the atomic number or the full name is necessary or assists an understanding.Nuclide: A nuclear species.

CHAPTER 2
Radioactivity and radiation

2.1 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 unstable and decay by emitting radiations of three main types, called alpha, beta and gamma radiation.

During the same period, scientists in several countries were experimenting with electrical discharge tubes known as Crookes tubes and investigating the fluorescence that occurred in the glass walls of the tubes. In 1895, the German physicist Wilhelm Conrad Rontgen discovered that the tubes were emitting invisible rays, which he named *X-rays*, that were capable of penetrating solid objects. The potential importance of this discovery, particularly in the medical field, was quickly appreciated and within weeks investigators in many countries were developing equipment and techniques to exploit the discovery. The first medical X-ray was taken by Rontgen himself and was of his wife's hand (see Figure 2.1). When Frau Rontgen saw the photograph, she exclaimed 'I have seen my death!'

Figure 2.1 The first medical X-ray.

2.2 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 four units and carries two units of positive charge (Figure 2.2).

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^-.

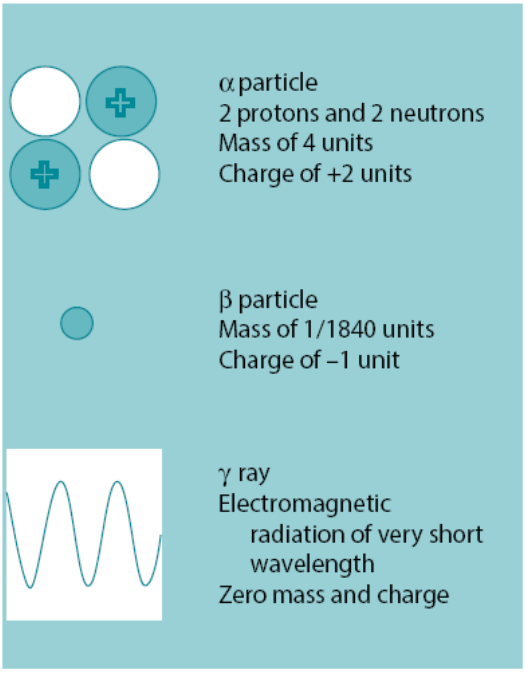


Figure 2.2 α, β and γ radiation.

Gamma (γ) radiation is electromagnetic in nature, like light and radio waves, but nevertheless can be described as consisting of 'particles' called **photons**. These photons do not have any mass or electrical charge but consist of packets (or 'quanta') of energy transmitted in the form of a wave motion (wave packets). 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 $E \propto 1/\lambda$, where E is the energy of the quantum or photon of electromagnetic radiation and λ is its wavelength. The X-rays discovered by Rontgen are in most respects identical to γ radiation, the essential difference between the two types of radiation being only in their origin. Whereas γ 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 Figure 2.3.

All electromagnetic radiations travel through free space with the same velocity of 3×10^8 metres per second – called 'the speed of light in a vacuum'. Their velocity decreases in dense media, but in air the decrease is negligible.

2.3 ELECTRONVOLT

Radiation energy is expressed in **electronvolts** (eV). One electronvolt is the energy gained by an electron in passing through an electrical potential of 1 volt (V). For example, in an X-ray tube, electrons are accelerated from a heated tungsten filament through an electrical potential of typically 100,000 V 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

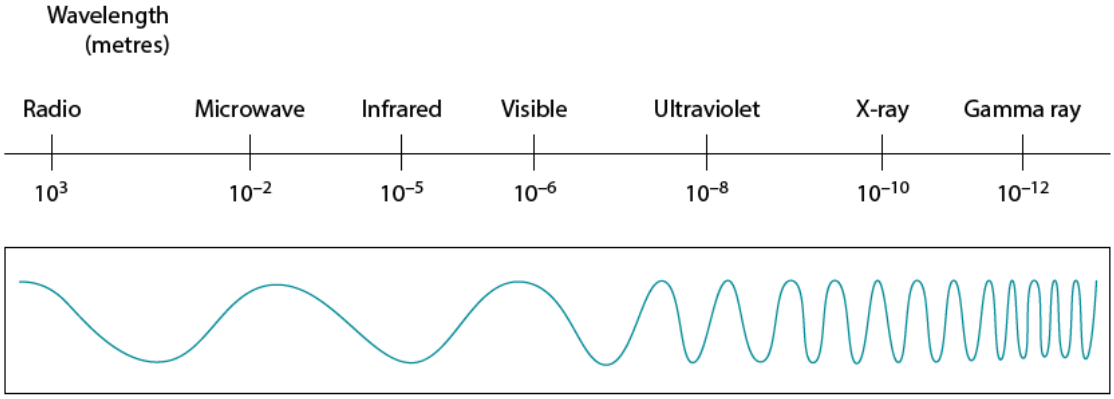


Figure 2.3 The electromagnetic spectrum.

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 (E_K) of a particle of mass (m) travelling with velocity (v) which is much smaller than the velocity of light is given by the equation

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

(A correction is necessary for particles which have velocities approaching the velocity of light.) Because of its much smaller mass, 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.

2.4 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 (U-238) has 92 protons and 146 neutrons. To achieve greater stability, the nucleus may emit an α 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 has become an isotope of the element thorium (Th), with a mass number of 234, namely Th-234. This decay process may be represented as follows:

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

or, more commonly

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

It was pointed out in Chapter 1 that, apart from the few lightest elements, there are more neutrons than protons in the nucleus and the difference becomes greater with increasing atomic number. Alpha emission reduces the number of each by two, but the proportionate reduction is considerably less for neutrons than for protons. In the U-238 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. To correct this instability, the nucleus does not simply eject a neutron (or neutrons). Instead, one of the neutrons in the nucleus changes into a proton by emitting a β particle, that is, a high-speed electron:

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

This phenomenon is known as **β emission**. In the case of Th-234, formed by the α decay of

uranium-238, the nucleus further decays by β emission to protactinium-234 (Pa-234):

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

or

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

Another example of this successive radioactive decay by α and β emission is

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

Here, polonium-218 (Po-218) decays by α-emission to lead-214 (Pb-214) which then decays by β-emission to bismuth-214 (Bi-214), which is also unstable and so further α- and β-decay processes occur until a stable atom is produced.

An α particle emitted by a nucleus has a discrete energy which is characteristic of the particular nucleus. However, 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 1/3 E_{max} (see Figure 2.4).

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

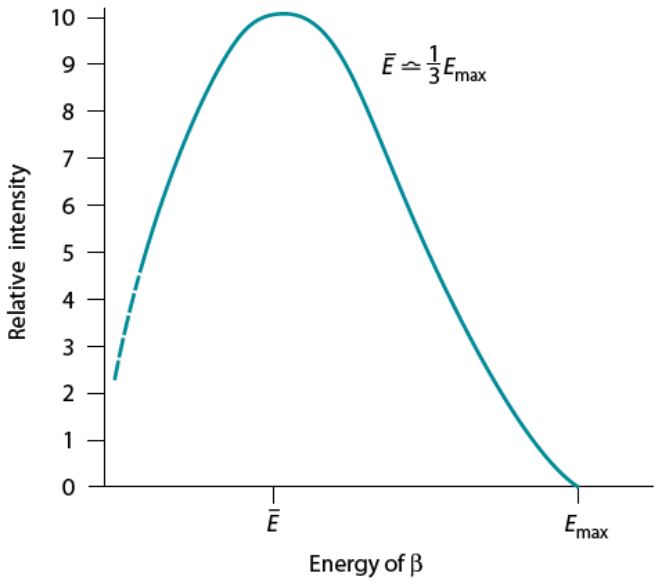


Figure 2.4 Typical beta spectrum.

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

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

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

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

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:

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

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

As will be discussed in more detail in Section 2.7, the rate at which a particular unstable species decays is characteristic of that species and can be expressed in terms of its **half-life**. This is the time for half of the atoms to decay. In a further half-life, half of the remaining atoms will decay and so on. Half-lives range from fractions of a second to billions of years.

2.5 NATURAL RADIOACTIVE SERIES

Apart from Na-22, the preceding examples of radioactive decay are all naturally occurring radioactive substances and belong to the so-called **natural radioactive series**. As discussed in Chapter 1, Section 1.4, the heavier elements were created by nucleosynthesis in earlier generations of stars, and the sun and solar system contain some of this material. All of the elements above lead (Z = 82) in the periodic table are unstable and most have long since decayed to negligible levels. However, a few with very long half-lives (a few hundred million years or more) remain at significant levels and these are Th-232, U-235 and U-238. Each of these is at the head of a chain in which a nucleus undergoes, over a period

of time, a series of α and β decays until it reaches stability as the nucleus of an atom of the element lead. These three chains form the natural radioactive series, called the thorium, uranium–radium and actinium series (see Table 2.1).

For completeness, this table also includes the neptunium series, at the head of which is neptunium-237 (Np-237) which has a half-life ($T_{1/2}$) of 2.2×10^6 y. This is much less than the age of the Earth and so the series has long since decayed. However, Np-237 is produced artificially in nuclear reactors and can be important in some situations.

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 Th-232 and this undergoes a series of radioactive decays as follows:

$$^{232}_{90}\text{Th} \xrightarrow{\alpha} {}^{228}_{88}\text{Ra} \xrightarrow{\beta^-} {}^{228}_{89}\text{Ac} \xrightarrow{\beta^-}$$
$$^{228}_{90}\text{Th} \xrightarrow{\alpha} {}^{224}_{88}\text{Ra} \xrightarrow{\alpha}$$
$$^{220}_{86}\text{Rn} \xrightarrow{\alpha} {}^{216}_{84}\text{Po} \xrightarrow{\alpha} {}^{212}_{82}\text{Pb} \xrightarrow{\beta^-} {}^{212}_{83}\text{Bi} \xrightarrow{\beta^-}$$
$$^{212}_{84}\text{Po} \xrightarrow{\alpha} {}^{208}_{82}\text{Pb}$$

The half-lives of these members of the decay series range from 0.15 s for Po-216 to about 1.4×10^{10} y for Th-232.

Apart from the radioactive species forming the natural series, there are a few other isotopes that have long enough half-lives to have survived from primordial times. The only one considered to be of practical significance is potassium-40 (K-40) which has a half-life of 1.3×10^9 y. Because it behaves chemically in the same way as stable potassium, it is present in living matter, including the human body, and makes a small contribution to radiation dose (see Chapter 5, Section 5.4).

Table 2.1 Natural radioactive series

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

2.6 INDUCED RADIOACTIVITY

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

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

On a practical note, this is an important reaction in the context of nuclear engineering since all steel alloys contain cobalt, which comprises 100% Co-59. Irradiation of the steels in the reactor core and structure produces Co-60, which is a significant contributor to the radiation exposure of operators.

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

2.7 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 $N_t = N_0/2$ in the preceding equation

$$N_0/2 = N_0 e^{-\lambda T½}$$

and then dividing across by N_0 and taking logs

$$\log_e(1/2) = -\lambda T_{1/2}$$

Now

$$\log_e(1/2) = -\log_e(2)$$

and so

$$T_{1/2} = \frac{\log_e 2}{\lambda} = \frac{0.693}{\lambda}$$

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 2.5, 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. This is illustrated in more detail in Chapter 11, Section 11.2.3. The half-life of a particular radioactive isotope is constant and its measurement assists in the identification of radioactive samples of unknown composition. 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 (Po-212) to about 10^{17} years (Bi-209), which represents a factor of 10^{31}.

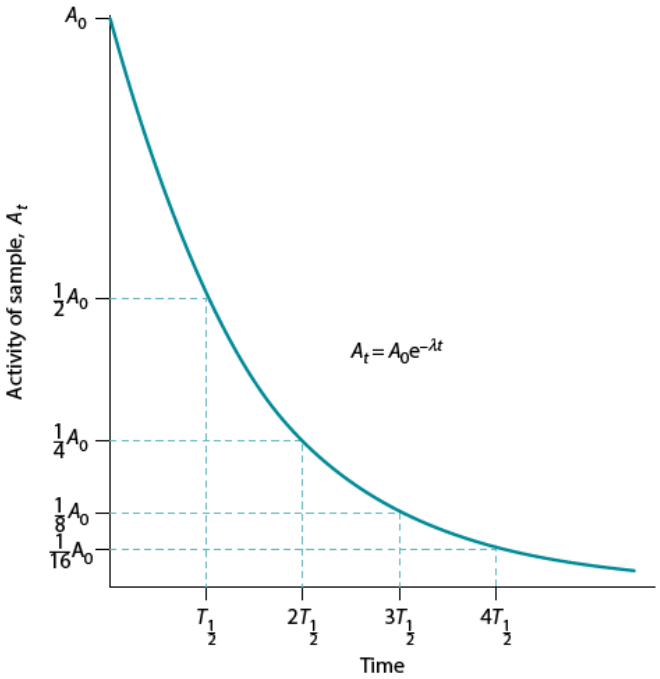


Figure 2.5 Variation of activity with time.

For many years, the unit of radioactivity was the **curie** (Ci), 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 per second (dps), which is almost the same:

1 Ci = 3.7×10^{10} dps or 2.22×10^{12} disintegrations per minute (dpm)

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:

1 becquerel (Bq) = 1 dps
1 kilobecquerel (kBq) = 10^3 Bq = 10^3 dps
1 megabecquerel (MBq) = 10^6 Bq = 10^6 dps
1 gigabecquerel (GBq) = 10^9 Bq = 10^9 dps
1 terabecquerel (TBq) = 10^{12} Bq = 10^{12} dps
1 petabecquerel (PBq) = 10^{15} Bq = 10^{15} dps

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.

2.8 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 2.6. 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 2.6, all the nuclides on the same horizontal line have the same atomic number, whereas 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 2.6 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 Na-23 produces Na-24 and this decays with a half-life of 15.0 h by emitting β^- particles of 1.39 MeV and γ rays of 2.75 and 1.37 MeV. The nucleus resulting from the decay of Na-24 is magnesium-24 (Mg-24), which is stable.

It can be seen that the nuclide chart is an extremely valuable source of information on the properties of both stable and unstable nuclides. A complete chart with detailed information can be found at *https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html*.

2.9 INTERACTION OF RADIATION WITH MATTER

2.9.1 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), as will be discussed further in Chapter 3. Another important effect is that when charged particles are slowed down very rapidly, they

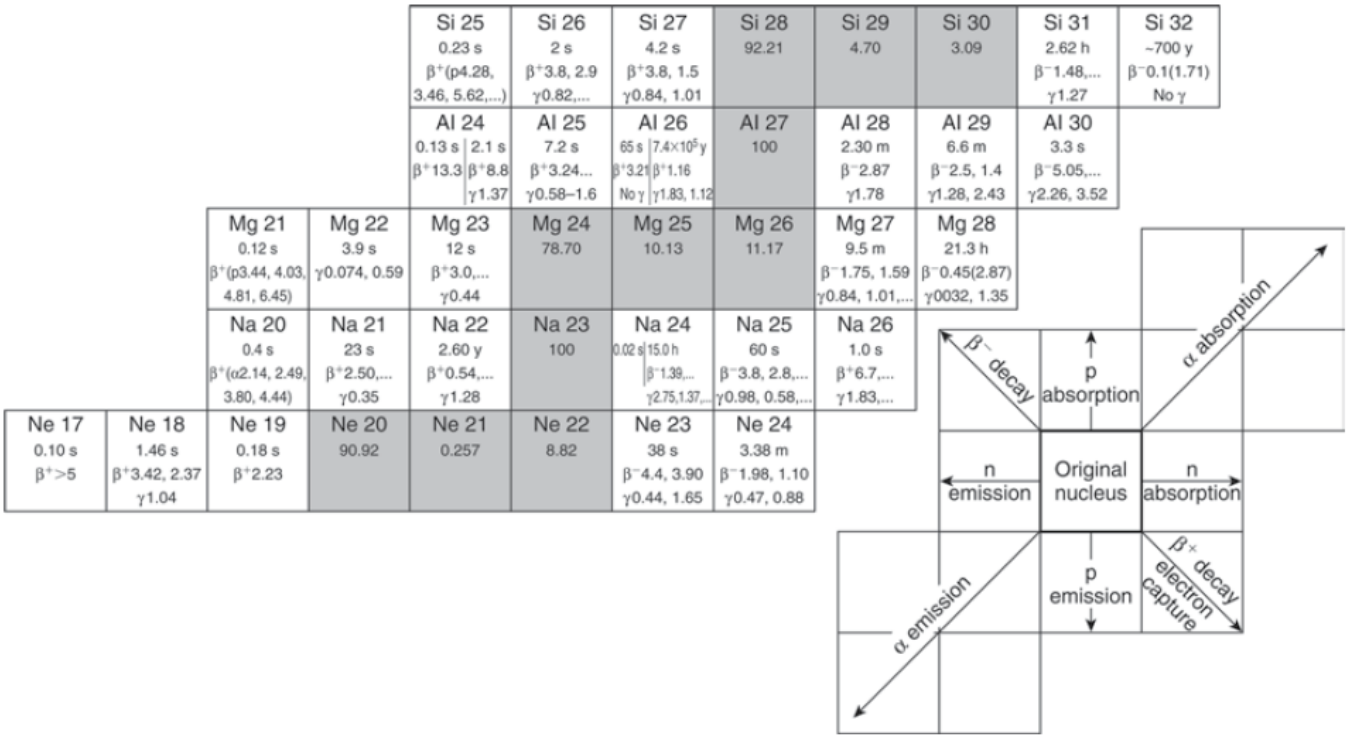


Figure 2.6 A portion of the nuclide chart.

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.

2.9.2 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 an 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 2.9.1.

2.9.3 NEUTRONS

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. These processes are described in greater detail in Chapter 8, Section 8.5.

Table 2.2 summarizes the types of interactions of nuclear radiations with matter.

2.10 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 have a greater range than α particles in dense media.

Gamma radiation loses its energy mainly by interacting with atomic electrons and is able to penetrate large distances even in dense media.

Neutrons give up their energy through a variety of interactions, the relative importance 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 2.3. The ranges are only approximate since they depend on the energy of the radiation.

Table 2.2 Interactions of nuclear radiations

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	Photon is completely absorbed
	b. Compton effect c. Pair production	Only part of the photon energy is absorbed
Neutron	a. Elastic scattering b. Inelastic scattering c. Capture processes	Discussed in Chapter 8

When radiation strikes matter, both the nature of the radiation and the composition of the matter affect what happens. The process begins with the transfer of radiation energy to the atoms and molecules, heating the matter or even modifying its structure.

If all the energy of a bombarding particle or photon is transferred, the radiation will appear to have been stopped within the irradiated matter. Conversely, if the energy is not completely deposited in the matter, the remaining energy will emerge as though the matter were transparent or at least translucent. This said, we shall now introduce some of the physical phenomena that are involved as radiation interacts with matter, and in particular we shall consider, separately at first, the interactions in matter of both photons (gamma rays and X-rays) and charged particles (alpha and beta particles).

Interaction of photons with matter

As they pass through matter, photons interact with atoms. The type of interaction is a function of the energy of the photons and the atomic number (Z) of the elements composing the matter.

Types of photon interactions in matter

In the practice of nuclear medicine, where gamma rays with energies between 50 and 550 keV are used, **Compton scattering** is the dominant type of interaction in materials with lower atomic numbers, such as human tissue (Z = 7.5). The **photoelectric effect** is the dominant type of interaction in materials with higher atomic numbers, such as lead (Z = 82). A third type of interaction of photons with matter, **pair production**, only occurs with very high photon energies (greater than 1020 keV) and is therefore not important in clinical nuclear medicine. Figure 2.1 depicts the predominant types of interaction for various combinations of incident photons and absorber atomic numbers.

Compton scattering

In Compton scattering, the incident photon transfers part of its energy to an outer-shell or (essentially) "free" electron, ejecting it from the atom. Upon ejection, this electron is called a **Compton electron**. The photon, which has lost energy in the interaction, is scattered (Figure 2.2) at an angle that depends on the amount of energy transferred from the photon to the electron. The scattering angle can range from nearly 0° to 180°. Figure 2.3 illustrates scattering angles of 135° and 45°.

Photoelectric effect

An incident photon may also transfer its energy to an orbital (generally inner-shell) electron. This process is called the photoelectric effect and the ejected electron is called a **photoelectron** (Figure 2.4). This electron leaves the atom with an energy equal to the energy of the incident gamma ray diminished by the binding energy of the electron. An outer-shell electron then fills the inner-shell vacancy, and the excess energy is emitted as an X-ray:

$$E_{\text{photoelectron}} = E_{\text{photon}} - E_{\text{binding}}$$

Table 2.1 lists the predominant photon interactions in some common materials.

Answers

1. (a) and (c) are true, (b) is false; alpha particles have a shorter range than beta particles.
2. True.
3. False: Compton scattering is the dominant interaction.
4. (1) (b). (2) (a). (3) (c).
5. (b), (c), (d), (f).
6. (a), (c), (e), (g).
7. (a).
8. (a), (d), (e).
9. (a).
10. (b).
11. 0.21.

Questions

1. Which of the following is true of the interaction of charged particles with matter?
   (a) Alpha particles have a higher LET than beta particles.
   (b) The range of alpha particles is generally greater than that of beta particles.
   (c) Alpha particles have a higher specific ionization than beta particles.

2. True or false: Bremsstrahlung is X-ray radiation emitted as a moving electron or positron slows down and is deflected in close proximity to a nucleus.

3. True or false: The photoelectric effect is the dominant type of photon interaction in tissue for the radionuclides used in the practice of nuclear medicine.

4. For each of the terms listed here, select the appropriate definition:
   (1) HVL (half-value layer).
   (2) TVL (tenth-value layer).
   (3) μ (mu) (linear attenuation coefficient).
      (a) The thickness of an attenuator that will reduce the intensity (number of photons) in a monoenergetic beam by 90%.
      (b) The thickness of an attenuator that will reduce the intensity (number of photons) in a monoenergetic beam by 50%.
      (c) 0.693/HVL.

5. Which of the following occur during photon interactions with matter (more than one answer may apply)?
   (a) Excitation.
   (b) Pair production.
   (c) Ionization.
   (d) Compton scattering.
   (e) Bremsstrahlung.
   (f) Photoelectric effect.
   (g) Annihilation reaction.

6. Which of the following occur during charged-particle interactions with atoms (more than one answer may apply)?
   (a) Excitation.
   (b) Pair production.
   (c) Ionization.
   (d) Compton scattering.
   (e) Bremsstrahlung.
   (f) Photoelectric effect.
   (g) Annihilation reaction.

7. Which of the following are true about the annihilation reaction?
   (a) The conversion of the mass of the positron and electron into energy is an example of the interchangeability of mass and energy as described by Einstein's famous equation $E = mc^2$.
   (b) Two oppositely directed 450 keV photons are emitted as a result of the annihilation reaction.
   (c) Both (a) and (b).

8. Which of the following are referred to as non-penetrating radiation?
   (a) Positrons.
   (b) Gamma photons.
   (c) X-rays.
   (d) Alpha particles.
   (e) Beta particles.

9. Which term refers to the loss of energy or weakening of a beam of radiation as it passes through matter?
   (a) Attenuation.
   (b) Absorption.

10. Which term is used to describe the transfer of energy from radiation to surrounding matter?
    (a) Attenuation.
    (b) Absorption.

11. You shield a sample of ^{99m}Tc using a 1 mm-thick sheet of lead. What fraction of emissions is blocked by the lead? The linear attenuation coefficient μ of lead for 140 keV photons is 23.1 cm^{-1}.

2.11 Radioactive Decay

In 1896, Henri Becquerel first discovered natural radioactivity in potassium uranyl sulfate. Artificial radioactivity was not produced until 1934, when I. Curie and F. Joliot made boron, aluminum, and magnesium radioactive by bombarding them with a-particles from polonium. Radionuclides are unstable and decay by emission of particle or γ- radiation to achieve stable configuration of protons and neutrons in the nucleus. As already mentioned, the stability of a nuclide in most cases is determined by the N/Z ratio of the nucleus. Thus, as will be seen later, whether a nuclide will decay by a particular particle emission or γ-ray emis- sion is determined by the N/Z and/or excitation energy of the nucleus. Radionuclides can decay by one or more of the six modes: spontaneous fission, isomeric transition (IT), alpha (α) decay, beta (β −) decay, positron (β +) decay, and electron capture (EC) decay. In all decay modes, energy, charge, and mass are conserved. Different decay modes of radionuclides are described later in detail.

Spontaneous Fission

Fission is a process in which a heavy nucleus breaks into two fragments accompanied by the emission of two or three neutrons. The neutrons carry a mean energy of 1.5 MeV and the process releases about 200 MeV energy that appears mostly as heat.

Spontaneous fission occurs in heavy nuclei, but its probability is low and increases with mass number of the nuclei. The half-life for spontaneous fission is 2 × 1017 years for ^{235}U and only 55 days for ^{254}Cf. As an alternative to the spontaneous fission, the heavy nuclei can decay by a-particle or g-ray emission.

Isomeric Transition

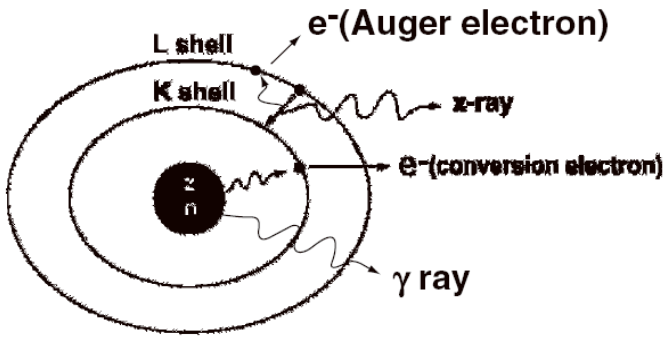
A nucleus can exist in different energy or excited states above the ground state, which is considered as the state involving the arrangement of protons and neutrons with the least amount of energy. These excited states are called the isomeric states and have lifetimes of fractions of picoseconds to many years. When isomeric states are long-

lived, they are referred to as metastable states and denoted by "m" as in ^{99m}Tc. An excited nucleus decays to a lower energy state by giving off its energy, and such transitions are called isomeric transitions (ITs). Several isomeric tran- sitions may occur from intermediate excited states prior to reaching the ground state. As will be seen later, a parent radionuclide may decay to an upper isomeric state of the product nucleus by α-particle or β-particle emission, in which case the isomeric state returns to the ground state by one or more isomeric transitions. A typical isomeric transition of ^{99m}Tc is illustrated in Figure 2.1. Isomeric transitions can occur in two ways: gamma (γ)-ray emission and internal conversion.

Gamma (γ)-Ray Emission

The common mode of an isomeric transition from an upper energy state of a nucleus to a lower energy state is by emission of an electromagnetic radiation, called the γ -ray. The energy of the γ-ray emitted is the difference between the two isomeric states. For example, a decay of a 525-keV isomeric state to a 210-keV isomeric state will result in the emission of a 315-keV γ -ray.

The excitation energy of the nucleus is transferred to a *K*-shell electron, which is then ejected, and the *K*-shell vacancy is filled by an electron from the *L* shell. The energy difference between the *L* shell and *K* shell appears as the characteristic *K* x-ray. Alternatively, the characteristic K x-ray may transfer its energy to an L-



shell electron, called the Auger electron, which is then ejedted.

Internal Conversion

An alternative to the γ-ray emission is the *internal conversion* process. The

excited nucleus transfers the excitation energy to an orbital electron-preferably the *K*-shell electron-of its own atom, which is then ejected from the shell, provided the excitation energy is greater than the binding energy of the electron (Fig. 2.2). The ejected electron is called the *conversion electron* and carries the kinetic energy equal to $E_g - E_B$, where E_g is the excitation energy and E_B is the binding energy of the electron. Even though the *K*-shell electrons are more likely to be ejected because of the proximity to the nucleus, the electrons from the *L* shell, *M* shell, and so forth also may undergo the internal conversion process. The ratio of the number of conversion electrons (N_e) to the number of observed γ-radiations (N_g) is **Alpha (α)-Decay**

The α-decay occurs mostly in heavy nuclides such as uranium, radon, plutonium, and so forth. Beryllium-8 is the only lightest nuclide that decays by

$$^{222}_{86}\mathrm{Rn} \rightarrow {}^{218}_{84}\mathrm{Po} + \alpha$$

breaking up into two α-particles. The α-particles are basically helium ions with two protons and two neutrons in the nucleus and two electrons removed from the helium atom. After α-decay, the atomic number of the nucleus is reduced by 2 and the mass number by 4.

The α-particles from a given radionuclide all have discrete energies corresponding to the decay of the initial nuclide to a particular energy level of the product (including, of course, its ground state). The energy of the α- particles is, as a rule, equal to the energy difference between the two levels and ranges from 1 to 10 MeV. The α-particles can be stopped by a piece of paper, a few centimeters of air, and gloves.

Beta (β^-)-Decay

When a radionuclide is neutron rich-that is, the *N*/*Z* ratio is greater than that of the nearest stable nuclide-it decays by the emission of a β^-- particle and an antineutrino. In the β^--decay process, a neutron is converted to a proton, thus

raising the atomic number Z of the product by 1. Thus:

$$n \rightarrow p + \beta^{-} + \bar{\nu}$$

The difference in energy between the parent and daughter nuclides is called the *transition or decay energy*, denoted by E_{max}. The β^--particles carry E_{max} or part of it, exhibiting a spectrum of energy as shown in Figure 2.3. The average energy of the β^--particles is about one-third of E_{max}. This obser- vation indicates that β^--particles often carry only a part of the transition energy, and energy is not apparently conserved in β^--decay. To satisfy the law of energy conservation, a particle called the *antineutrino* ν, with no charge and a negligible mass has been postulated, which carries the remainder of E_{max} in each β^--decay. The existence of antineutrinos has been proven experimentally.

After β^--decay, the daughter nuclide may exist in an excited state, in which case, one or more γ-ray emissions or internal conversion will occur to dispose of the excitation energy. In other words, β^--decay is followed by isomeric transition if energetically permitted.

The decay process of a radionuclide is normally represented by what is called the *decay scheme*. Typical decay schemes of ^{131}I and ^{99}Mo are shown in Figures

Positron (β^+)-Decay

When a radionuclide is proton rich-that is, the N/Z ratio is low relative to that of the nearest stable nuclide-it can decay by positron (β^+) emission accompanied by the emission of a neutrino (ν), which is an opposite entity of the antineutrino. Positron emission takes place only when the energy difference (transition energy) between the parent and daughter nuclides is greater than 1.02 MeV. In β^+-decay, essentially a proton is converted to a neutron plus a positron, thus, decreasing the atomic number Z of the daughter nuclide by 1. Thus,

$$p \rightarrow n + \beta^{+} + \nu$$

The requirement of 1.02 MeV for β^+-decay arises from the fact that one electron mass has to be added to a proton to produce a neutron and one positron is created. Since each electron or positron mass is equal to 0.511 MeV, one electron and one positron are equal to 1.02 MeV, which is required as a minimum for β^+-decay.

Some examples of β^+-decay follow:

^{18}The energetic β^+-particle loses energy while passing through matter. The range of positrons is short in matter. When it loses almost all of its energy, it combines with an atomic electron of the medium and is annihilated, giving rise to two photons of 511 keV emitted in opposite directions. These photons are called *annihilation radiations*.

The decay scheme of ^{68}Ga is presented in Figure 2.6. Note that the β^+-decay is represented by a two-step right-to-left arrow.

Fig. 2.6. Decay scheme of ^{68}Ga. The positrons are annihilated in medium to give rise to two 511-keV γ-rays emitted in opposite directions.

1.1. Electron Capture

Decay by electron capture (EC) is an alternative to the β^+-decay for protonrich radionuclides with N/Z lower than that of the stable nuclide. In EC decay, an electron from an extranuclear shell, particularly the K shell because of its proximity, is captured by a proton in the nucleus, forming a neutron accompanied by the emission of a neutrino for conservation of energy. Thus,

$$p + e^{-} \rightarrow n + \nu$$

General Equation

Radionuclides decay by spontaneous fission, α-, β^--, and β^+-particle emissions, electron capture, or isomeric transition. The radioactive decay is a random process, and it is not possible to tell which atom from a group of atoms disintegrates at a specific time. Thus, one can only talk about the average number of radionuclides disintegrating during a period of time.

This gives the disintegration rate of a particular radionuclide.

The disintegration rate of a radionuclide, that is, the number of disintegrations per unit time, given as $-dN/dt$, is proportional to the total number of radioactive atoms present at that time. Mathematically,

$$-dN/dt = \lambda N \qquad (3.1)$$

where N is the number of radioactive atoms present, and λ is referred to as the *decay constant* of the radionuclide. As can be seen from Eq. (3.1), it is a small fraction of the radioactive atoms that decays in a very short period of time. The unit of λ is $(\text{time})^{-1}$. Thus, if λ is 0.2 sec^{-1} for a radionuclide, then 20% of the radioactive atoms present will disappear per second.

The disintegration rate $-dN/dt$ is referred to as the *radioactivity* or simply the *activity* of the radionuclide and denoted by A. It should be understood from Eq. (3.1) that the same amount of radioactivity means the same dis- integration rate for any radionuclide, but the total number of atoms present and the decay constants differ for different radionuclides. For example, a radioactive sample A containing 10^6 atoms and with $\lambda = 0.01\ \text{min}^{-1}$ would give the same disintegration rate (10,000 disintegrations per minute) as that by a radioactive sample B containing 2×10^6 atoms and with a decay constant $0.005\ \text{min}^{-1}$.

Now from the preceding discussion, the following equation can be written:

$$A = \lambda N \qquad (3.2)$$

From a knowledge of the decay constant and radioactivity of a radionuclide, one can calculate the total number of atoms or mass of the radionuclides present (using Avogadro's number $1\ \text{g} \cdot \text{atom} = 6.02 \times 10^{23}$ atoms).

Because Eq. (3.1) is a first-order differential equation, the solution of this equation by integration leads to

$$N_t = N_0 e^{-\lambda t} \qquad (3.3)$$

where N_0 and N_t are the number of radioactive atoms at $t = 0$ and time t, respectively. Equation (3.3) is an exponential equation indicating that the radioactivity decays exponentially. By multiplying both sides of Eq. (3.3) by λ, one obtains

$$A_t = A_0 e^{-\lambda t} \qquad (3.4)$$

The factor $e^{-\lambda t}$ is called the *decay factor*. The decay factor becomes $e^{+\lambda t}$ if the activity at time t before $t = 0$ is to be determined. The plot of activity versus time on a linear graph gives

an exponential curve, as shown in Figure 3.1. However, if the activity is plotted against time on semilogarithmic paper, a straight line results, as shown in Figure 3.2.

Half-Life

Every radionuclide is characterized by a *half-life*, which is defined as the time required to reduce its initial activity to one half. It is usually denoted

The half-life of the radionuclide can be determined from the slope of the line, which is given as the decay constant λ. Alternatively, an activity and half its value and their corresponding times are read from the plot. The difference in the two time readings gives the half-life.

by $t_{1/2}$ and is unique for a radionuclide. It is related to the decay constant λ of a radionuclide by

$$\lambda = \frac{0.693}{t_{1/2}} \qquad (3.5)$$

(3.7)

Mean Life

Another relevant quantity of a radionuclide is its *mean life*, which is the average lifetime of a group of radionuclides. It is denoted by τ and is related to the decay constant λ and half-life $t_{1/2}$ as follows:

$$\tau = 1/\lambda \qquad (3.8)$$

$$\tau = t_{1/2}/0.693 = 1.44\ t_{1/2} \qquad (3.9)$$

In one mean life, the activity of a radionuclide is reduced to 37% of its initial value.

Effective Half-Life

As already mentioned, a radionuclide decays exponentially with a definite half-life, which is called the *physical half-life*, denoted by Tp (or $t_{1/2}$). The physical half-life of a radionuclide is independent of its physicochemical conditions. Analogous to physical decay, radiopharmaceuticals adminis- tered to humans disappear exponentially from the biological system through fecal excretion, urinary excretion, perspiration, or other routes. Thus, after in vivo administration every radiopharmaceutical has a *biolog- ical half-life* (T_b), which

is defined as the time needed for half of the radio- pharmaceutical to disappear from the biologic system. It is related to decay constant λ_b by $\lambda_b = 0.693/T_b$.

Obviously, in any biologic system, the loss of a radiopharmaceutical is due to both the physical decay of the radionuclide and the biologic elimination of the radiopharmaceutical. The net or effective rate (λe) of loss of radioactivity is then related to λ_p and λ_b by

$$\lambda_e = \lambda_p + \lambda_b \qquad (3.10)$$

Because $\lambda = 0.693/t_{1/2}$, it follows that

The effective half-life, T_e, is always less than the shorter of T_p or T_b. For a very long T_p and a short T_b, T_e is almost equal to T_b. Similarly, for a very long T_b and short T_p, T_e is almost equal to T_p. The unit of radioactivity is a curie. It is defined as 68 min).

$$\frac{1}{T_e} = \frac{1}{T_p} + \frac{1}{T_b} \qquad (3.11)$$

or,

$$T_e = \frac{T_p \times T_b}{T_p + T_b} \qquad (3.12)$$

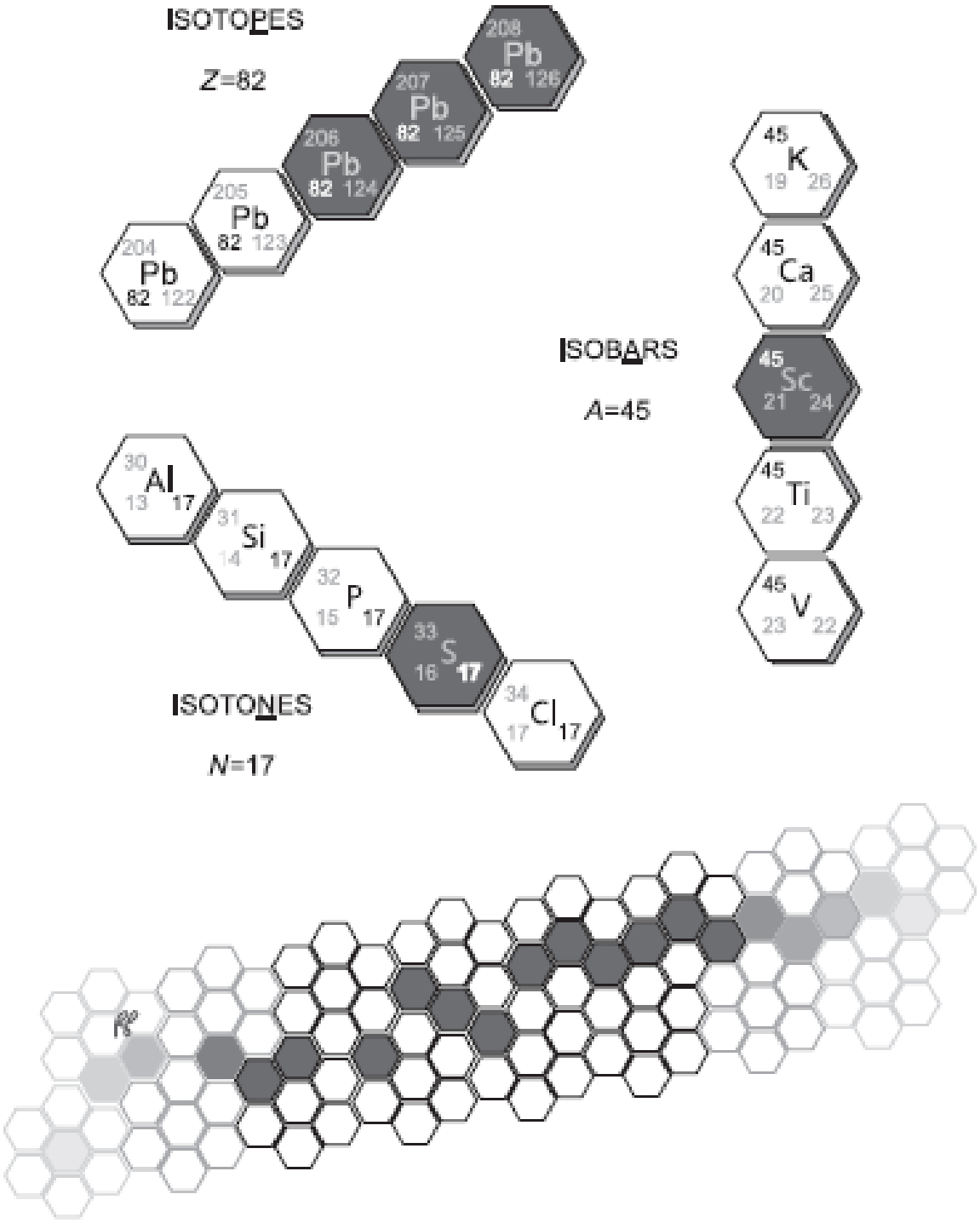


Figure 1.12 Nuclides of the same atomic number but different atomic mass are called isotopes, those of an equal number of neutrons are called isotones, and those of the same atomic mass but different atomic number are called isobars. Stable nuclear configurations are shaded gray, and radioactive configurations are white. (Adapted from Brucer, M., *Trilinear Chart of the Nuclides*, Mallinckrodt Inc., 1979.)

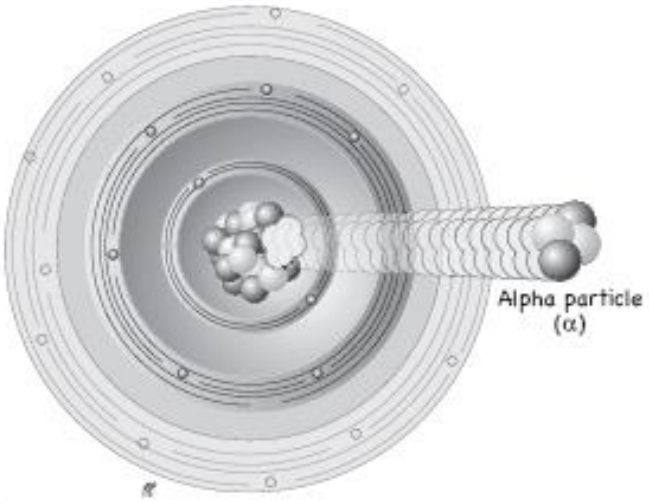


Figure 1.13 Alpha decay.

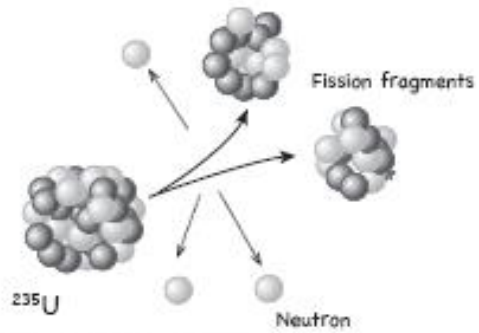


Figure 1.14 Fission of a ^{235}U nucleus.

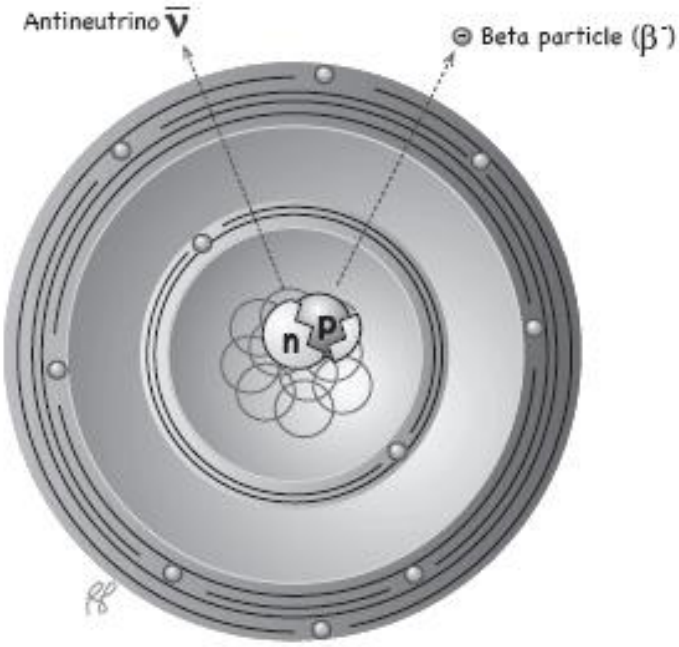


Figure 1.15 β^- (negatron) decay.

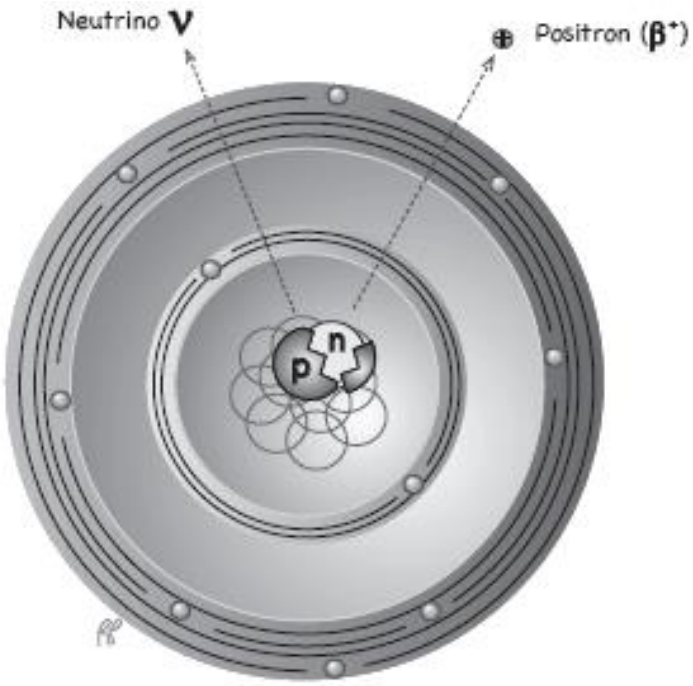


Figure 1.16 β^+ (positron) decay.

destroyed. Unless the difference between the masses of the parent and daughter atoms is at least equal to the mass of one electron plus one positron, a total equivalent to 1.02 MeV, there will be insufficient energy available for positron emission. Although the total energy emitted from an atom during beta decay or positron emission is constant, the relative distribution of this energy between the beta particle and antineutrino (or positron and neutrino) is variable. For example, the total amount of available energy released during beta decay of a hosphorus-32 atom is 1.7 MeV. This energy might be distributed as 0.5 MeV to the beta particle and 1.2 MeV to the antineutrino, or 1.5 MeV to the beta particle and 0.2 MeV to the antineutrino, or 1.7 MeV to the beta particle and no energy to the antineutrino, and so on. In any group of atoms, the likelihoods of occurrence of such combinations are not equal. It is very uncommon, for example, that all of the energy is carried off by the beta particle. It is much more common for the particle to receive less than half of the total amount of energy emitted. This is illustrated by Figure 1.17, a plot of the number of beta particles emitted at each energy from zero to the maximum energy released in the decay. Here, Eβ max is the maximum possible energy that a beta particle can receive during beta decay of any atom, and *E*_ is the average energy of all beta particles for decay of a group of such atoms. The average energy is approximately one-third of the maximum energy, shell electron then fills the vacancy in the inner shell left by the captured electron. The energy lost by the "fall" of the outer-shell electron to the inner shell is emitted as an X-ray.

Appropriate numbers of nucleons, but too much energy

Isomeric transition*:* Following alpha and beta decay and electron capture, the nucleus has a more favorable physical configuration of nucleons but usually contains an excess of energy. The nucleus is said to be in an excited state when the energy of the nucleus is greater than its resting level. If the excited state is stable enough (has a half-life longer than 10−12 seconds) then the nuclide is referred to as an isomer and the excess energy is shed by an isomeric transition. This may occur by either or both of two competing reactions: gamma emission and internal conversion. Most isomeric transitions occur as a combination of these two reactions.

Gamma emission: In this process, excess nuclear energy is emitted as a gamma ray (Figure 1.19). The name "gamma" was given to this radiation, before its physical nature was understood, because it was the third (alpha, beta, gamma) type of radiation discovered. A gamma ray is a photon (energy) emitted by an excited nucleus. Despite its unique name, it cannot be distinguished from photons of the same energy from a different source, for example X-rays.

Internal conversion: The excited nucleus can transfer its excess energy to an orbital electron (generally an inner-shell electron), causing the electron to be ejected from the atom. This can only occur if the excess energy is greater than the binding energy of the electron. This electron is called a **conversion electron** (Figure 1.20). The resulting inner-orbital vacancy is rapidly filled with an outer-shell electron (as the atom assumes a more stable state, inner orbitals are filled before outer orbitals). The energy released as a result of the "fall" of an outer-shell electron to an inner shell is emitted as an X-ray (Figure 1.20(a)) or as a free electron, an **Auger electron** (Figure 1.20(b)). Table 1.2 reviews the properties of the various subatomic particles.

Table 1.2 Properties of the subatomic particles

Name(s)	*Symbol*	*Mass*[a]	*Charge*
Neutron	n	1839	None
Proton	p	1836	Positive (+)
Electron	e^-	1	Negative (−)
Beta particle (beta-minus particle, electron)[b]	β^-	1	Negative (−)
Positron (beta-plus particle, positive electron)	β^+	1	Positive (+)
Gamma ray (photon)	γ	None	None
X-ray	X-ray	None	None
Neutrino	ν	Near zero	None
Antineutrino	$\overline{\nu}$	Near zero	None

[a]Relative to an electron.

[b]There is no physical difference between a beta particle and an electron; the term **beta particle** is applied to an electron that is emitted from a radioactive nucleus. The symbol β without a minus or plus sign attached always refers to a beta-minus particle, or electron.

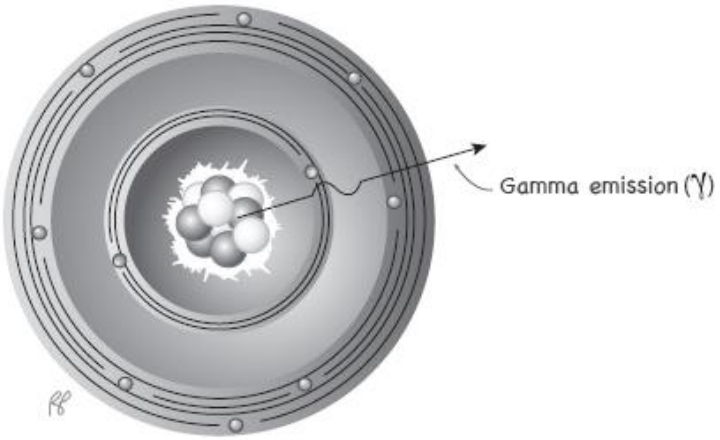


Figure 1.19 Isomeric transition. Excess nuclear energy is carried off as a gamma ray.

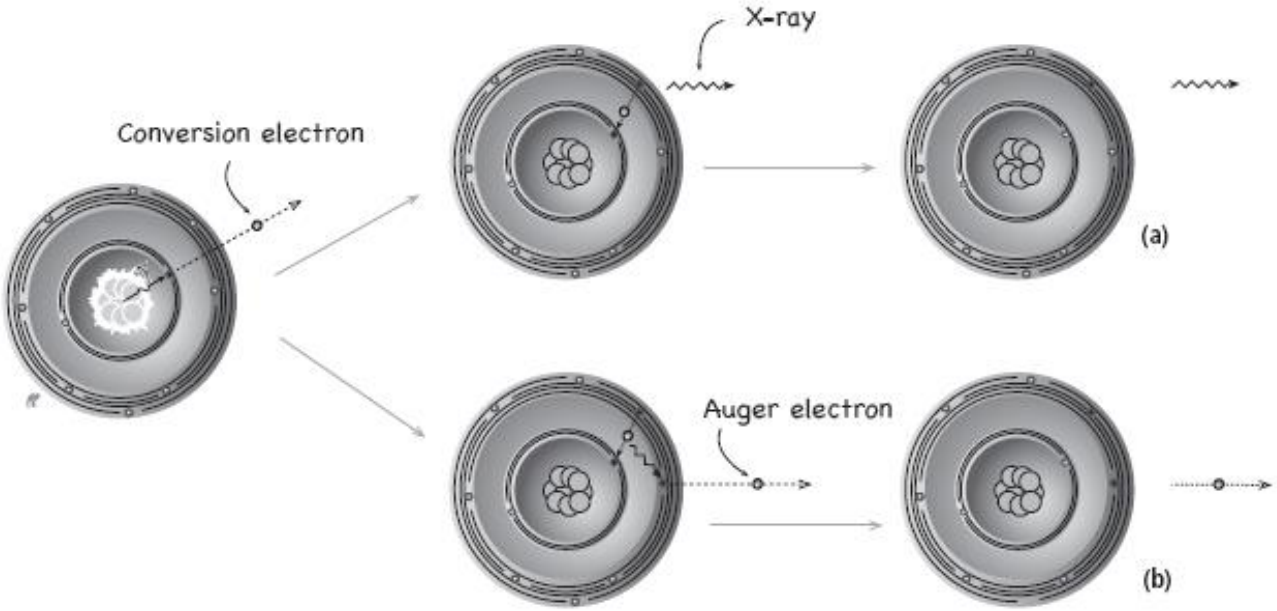


Figure 1.20 Internal conversion. As an alternative to gamma emission, it can lead to emission of either an X-ray (a) or an Auger electron (b).

Table 1.3 Conversion values for units of radioactivity

One curie (Ci) =		1×10^{3} mCi	1×10^{6} μCi	37×10^{9} Bq	37×10^{3} MBq
One millicurie (mCi) =	1×10^{-3} Ci		1×10^{3} μCi	37×10^{6} Bq	37 MBq
One microcurie (μCi) =	1×10^{-6} Ci	1×10^{-3} mCi		37×10^{3} Bq	37×10^{-3} MBq
One becquerel (Bq)[a] =	27×10^{-12} Ci	27×10^{-9} mCi	27×10^{-6} μCi		1×10^{-6} MBq
One megabecquerel (MBq) =	27×10^{-6} Ci	27×10^{-3} mCi	27 μCi	1×10^{6} Bq	

[a]One becquerel = 1 decay per second.

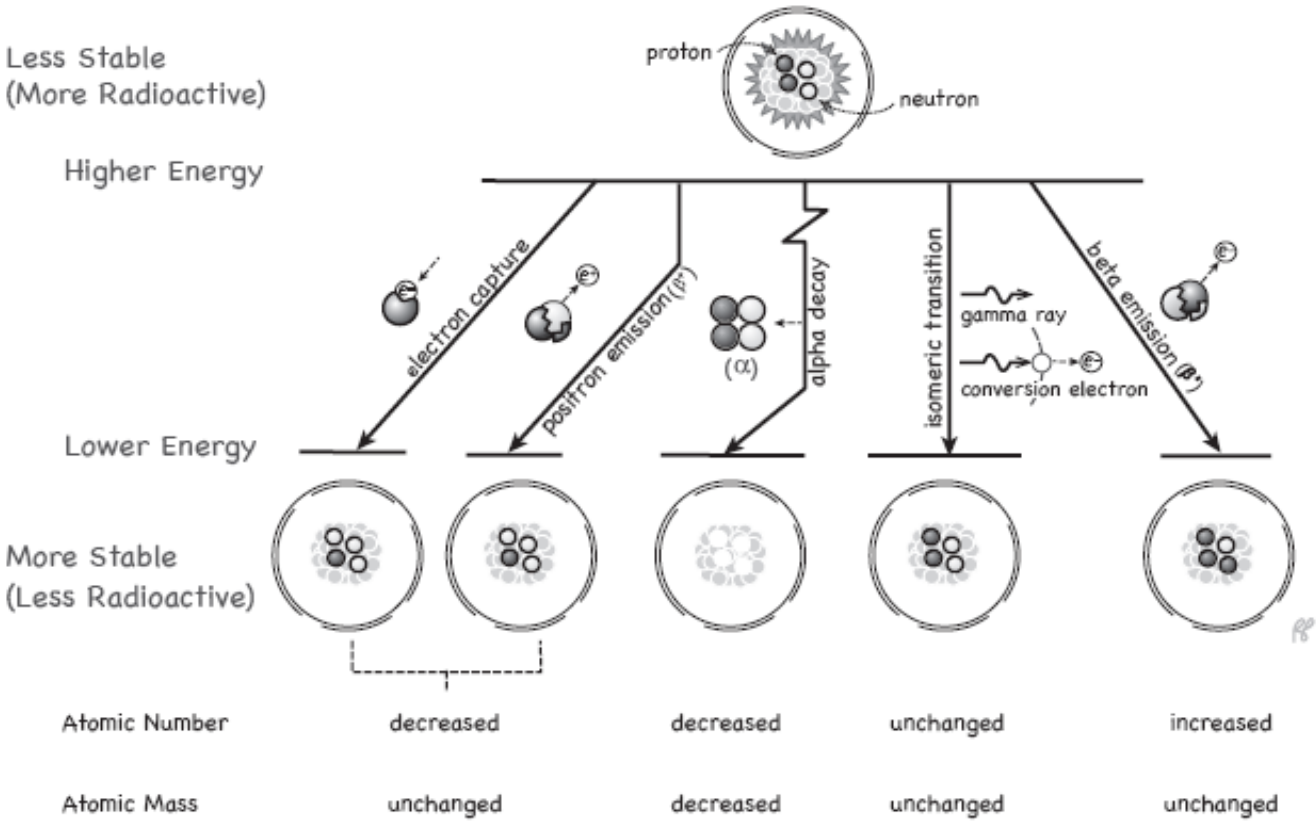


Figure 1.21 Decay schematics.

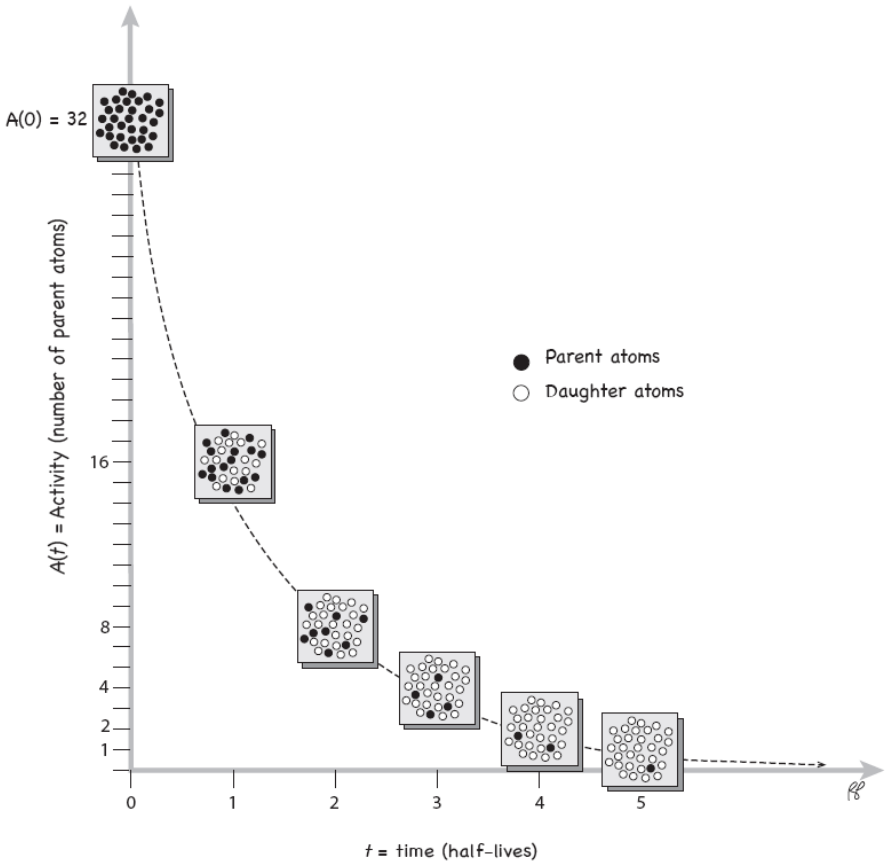


Figure 1.23 Decay curve. Note the progressive replacement of radioactive atoms (parent) by relatively more stable atoms (daughter) as shown schematically in each box.

Table 2.3 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, $E \propto 1/\lambda$, mass 0, charge 0.
- **Electronvolt:** Energy gained by an electron in passing through an electric potential of 1 V.

$$10^6 \text{ eV} \equiv 10^3 \text{ keV} \equiv 1 \text{ MeV}$$

- **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:

$$T_{1/2} = \frac{0.693}{\lambda}$$

- **Curie (Ci):** Former unit of radioactivity defined as 3.7×10^{10} dps.

$$1 \text{ Ci} \equiv 10^3 \text{ mCi} \equiv 10^6 \ \mu\text{Ci}$$

- **Becquerel (Bq):** SI unit of radioactivity, defined as 1 dps.

$$1 \text{ TBq} \equiv 10^6 \text{ MBq} \equiv 10^{12} \text{ Bq}$$

- **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 effect, and
  3. pair-production.

CHAPTER 3
Radiation units

3.1 ABSORPTION OF ENERGY

Just as heat and light transfer energy from the Sun to the Earth and the atmosphere, nuclear radiation transfers energy from a source to an absorbing medium. The source of nuclear radiation may be radioactive atoms or equipment such as X-ray machines. The effect of absorbing the more familiar types of radiation, such as heat, is to raise the temperature of the absorbing medium. If this medium is the human body, or part of it, the rise in temperature is sensed and, if it becomes excessive, avoiding action can be taken by sheltering under a sunshade (shielding), for example, or by moving farther away from a fire (distance). However, a dose of gamma (γ) radiation or other nuclear radiation that is large enough to be lethal to a human being would increase the body temperature by less than one-thousandth of 1°C. The body is therefore unable to sense even very high intensities of these types of radiation.

As discussed in Chapter 2, charged particles (such as α and β) and high-energy photons (X and γ radiation) deposit energy by interactions with atomic electrons in an absorbing medium. These radiations differ from other types, such as light and radio waves, in that each individual particle or photon has a sufficiently high energy to cause ionization of atoms in the cells of the human body. The high energy is due to the very high velocity of the particles or the short wavelength of the X and γ radiation.

3.2 IONIZATION

Ionization is the removal of an orbital electron from an atom. Since the electron has a negative charge, the atom is consequently left positively charged. The atom and the electron, so separated, are known as an **ion pair**, that is, a positive ion (the atom minus one electron) and a negative ion (the electron). To cause ionization requires energy and this is supplied by the absorption of radiation energy in the medium, which subsequently results in the production of ion pairs. The particles or photons of radiation lose their energy to the medium in the process. Figure 3.1 shows the ionization of a helium atom by an alpha (α) particle.

Normally, positive and negative ions recombine to form neutral atoms, and the energy originally given to the ion pair is converted into heat energy. If the absorbing medium is a gas, such as air, the ions can be prevented from recombining by applying an electrical field. This is done by applying a voltage between two plates (electrodes) with a gas gap between them. Figure 3.2 shows such a system, known as an ionization chamber, in which ion pairs are being produced along the track of an α particle. If the applied voltage is sufficiently high, negative ions produced in the volume between the electrodes are attracted to the positive electrode and positive ions to the negative electrode. The flow of ions to the respective electrodes constitutes an electrical current and, since this is proportional to the intensity of radiation, ion chambers provide a means of measuring radiation. It should be realized that, although only a

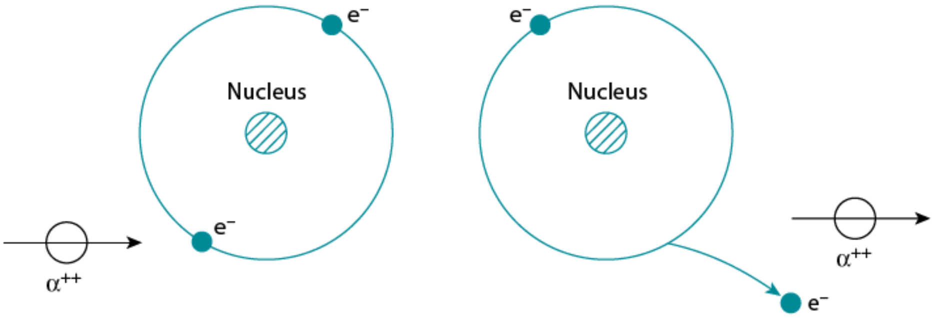


Figure 3.1 Ionization of a helium atom by an α particle.

few ion pairs are shown in the figure, in the case of beta (β) particles, several hundreds of ion pairs are formed per centimetre of track in air and, in the case of α particles, some tens of thousands.

In a medium such as water (of which the human body is largely composed), ionization can lead to breakdown of water molecules and the formation of chemical forms that are damaging to biological material. The harmful effects of radiation on the human system, which are described in Chapter 4, Section 4.4, are largely attributable to such chemical reactions.

As already mentioned, the ionization of a gas provides a means of detecting radiation and the first widely used radiation unit, the **roentgen**, was based on the ionizing effect on air of X and γ radiation. This unit had several limitations and so two further units, the **rad** and the **rem**, were introduced. Later, these two units were replaced in the SI system (Système International d'Unités) by the **gray** (Gy) and the **sievert** (Sv), respectively.

The gray and the sievert have been approved by the International Commission on Radiation Units and Measurements (ICRU) and used by the International Commission on Radiological Protection (ICRP). However, the older units, the rad and the rem, are still used in some countries, and an explanation of the relationships between the old units and the SI units is given in Appendix B.

3.3 ABSORBED DOSE

Absorbed dose is a measure of energy deposition in any medium by any type of ionizing radiation. The

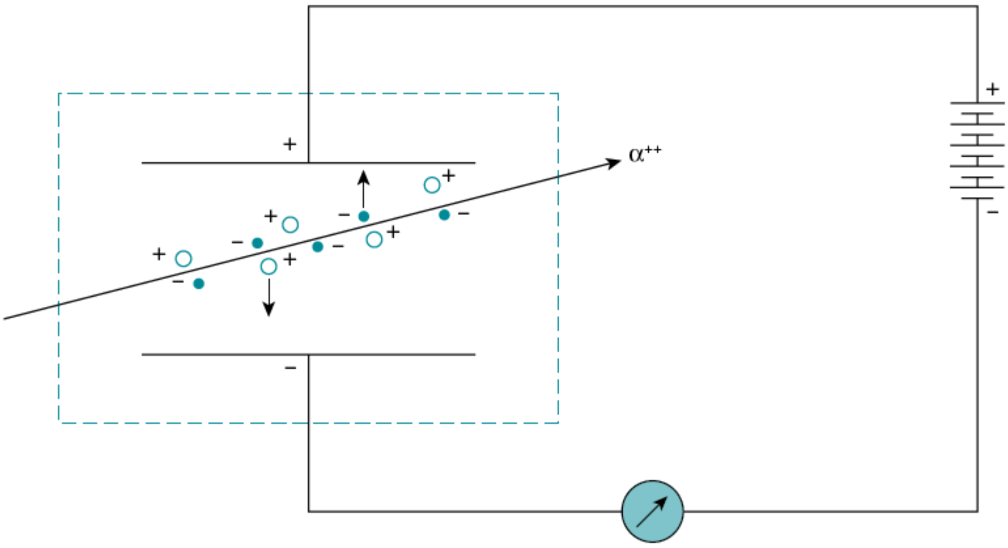


Figure 3.2 Ionization chamber system.

unit of absorbed dose in SI units is the gray and is defined as an energy deposition of 1 J/kg. Thus

$$1\,\text{Gy} = 1\,\text{J/kg}$$

When quoting an absorbed dose, it is important to specify the absorbing medium, for example air, water or tissue, as the rate of energy deposition varies considerably between different media.

3.4 EQUIVALENT DOSE

Although the quantity of absorbed dose is a very useful physical concept, it transpires that in biological systems the same degree of damage is not necessarily produced by the same absorbed dose of different types of radiation. It is found, for example, that 0.05 Gy of α radiation can do as much biological damage as 1 Gy of γ radiation. This difference in the radiobiological effectiveness must be taken into account if we wish to add doses of different radiations to obtain the total biologically effective dose. To do this, we must multiply the absorbed dose of each type of radiation by a **radiation weighting factor** (w_R), which reflects the ability of the particular type of radiation to cause damage. The quantity obtained when the absorbed dose is multiplied by the radiation weighting factor is known as the **equivalent dose**, H.

The unit of equivalent dose in SI units is the sievert, which is related to the gray as follows:

$$\text{Equivalent dose, H (Sv)} = \text{Absorbed dose (Gy)} \times w_R$$

The value of the radiation weighting factor is found to depend on the density of ionization caused by the radiation. An α particle produces about 10^6 ion pairs per millimetre of track in tissue, whereas a β particle produces about 10,000/mm. The radiation weighting factor is assigned a value of 1 for γ radiation and the values for other types of radiation are related to this in accordance with their ionization densities. β radiation causes ionization of a similar density to γ radiation and so its weighting factor is also 1. The value of the radiation weighting factor for neutrons depends on the neutron energy and is 2.5 for thermal neutrons and up to 20 for fast neutrons. For α and other particles with multiple charges, w_R is also taken as 20. The values of w_R for the most commonly encountered radiations are summarized in Table 3.1.

Table 3.1 Summary of values of radiation weighting factor

Type of radiation	Radiation weighting factor
X-rays, γ rays and electrons	1
Protons	5
Thermal neutrons	2.5
Fast neutrons	2.5–20[a]
α particles, fission fragments	20

[a] Depending on energy.

EXAMPLE 3.1

In 1 year a worker receives a γ dose of 0.01 Gy, a thermal neutron (N_s) dose of 0.002 Gy and a fast neutron dose (N_f) of 0.0002 Gy. What is his total equivalent dose? (Take the radiation weighting factor for fast neutrons as 20.)

Equivalent dose = Absorbed dose × Radiation weighting factor
Equivalent dose, γ = 0.01 × 1 = 0.01 Sv
Equivalent dose, N_s = 0.002 × 2.5 = 0.005 Sv
Equivalent dose, N_f = 0.0002 × 20 = 0.004 Sv

Total equivalent dose = 0.019 Sv

In the remainder of the book, we generally refer to **equivalent dose** simply as dose, except where this could lead to confusion.

3.5 EFFECTIVE DOSE

A further complication is that different organs and tissues have differing sensitivities to radiation. To deal with the very common situation in which the body is not uniformly exposed, another concept is needed to assist in combining the effects of exposure of different organs of the body to give an overall measure of the **detriment**. This is called **effective dose**, E, and is obtained by summing the equivalent doses to all tissues and organs of the body multiplied by a weighting factor w_T for each tissue or organ. This is written as follows:

$$E = \sum_T H_T w_T$$

where H_T is the equivalent dose in tissue T. The concept of detriment and the basis of the organ weighting factors is discussed further in Chapter 4, Section 4.8. It should be noted that effective dose is also expressed in units of sieverts.

3.6 SUBMULTIPLES

In terms of the levels of radiation exposure encountered in the working environment, the gray and the sievert are very large units. It is often convenient to have smaller units, and this is done by using the prefixes **milli** (one-thousandth), abbreviated m, and **micro** (one-millionth), abbreviated μ. Thus

$$1\ \text{Gy} = 1000\ \text{mGy} = 1{,}000{,}000\ \mu\text{Gy}$$

$$1\ \text{Sv} = 1000\ \text{mSv} = 1{,}000{,}000\ \mu\text{Sv}$$

EXAMPLE 3.2

During four successive weeks, a nuclear reactor operator received the following doses of γ radiation:

Week 1 350 μSv
Week 2 200 μSv
Week 3 420 μSv
Week 4 360 μSv

What was his total dose in mSv over the 4-week period?

Total dose over the 4-week period in μSv is

$$\begin{aligned} 350 + 200 + 420 + 360\ \mu\text{Sv} &= 1330\ \mu\text{Sv} \\ &= 1330/1000\ \text{mSv} \\ &= \mathbf{1.33\ mSv} \end{aligned}$$

3.7 DOSE RATE

Grays and sieverts are units that express an amount of radiation which may have been received over any period of time. In controlling the radiation hazard, it is usually necessary to know the rate at which the radiation is being received. The relationship between dose, **dose rate** and time is

$$\text{Dose} = \text{Dose rate} \times \text{Time}$$

Thus, if someone works in an area for 2 h and receives a dose of 80 μSv, then the dose rate in that area is 40 μSv/h. Similarly, absorbed dose rates are expressed in Gy/h.

EXAMPLE 3.3

If a person is permitted to receive a total dose of 200 μSv in a week, for how many hours during that week may they work in an area in which the dose rate is 10 μSv/h?

$$\text{Dose} = \text{Dose rate} \times \text{Time}$$

$$\text{Time} = \frac{\text{Dose}}{\text{Dose rate}}$$

$$\text{Time} = \frac{200\ \mu\text{Sv}}{10\ \mu\text{Sv/h}} = 20\ \text{h}$$

3.8 FLUX

It is often convenient to express a radiation field as the number of particles or photons crossing an area of 1 m² in 1 s. This is strictly called the **fluence rate**, but is commonly referred to as **flux** (denoted by Φ). The concept is best illustrated by a practical example.

Consider a point source which emits neutrons at the rate of Q per second (Figure 3.3). The flux at distance r is the number of neutrons per second passing through an area of 1 m². Since the neutrons are being emitted uniformly in all directions, the flux at distance r is the number of neutrons emitted per second divided by the area of the sphere of radius, r. This area is $4\pi r^2$ and so the flux Φ is given by

$$\Phi = \frac{Q}{4\pi r^2}\ \text{neutrons per square metre per second}\ (\text{n/m}^2/\text{s})$$

Note that if r is doubled, r^2 increases fourfold and Φ reduces fourfold. This relationship is the **inverse square law**, which will be dealt with in greater detail in Chapter 8, Section 8.3.1.

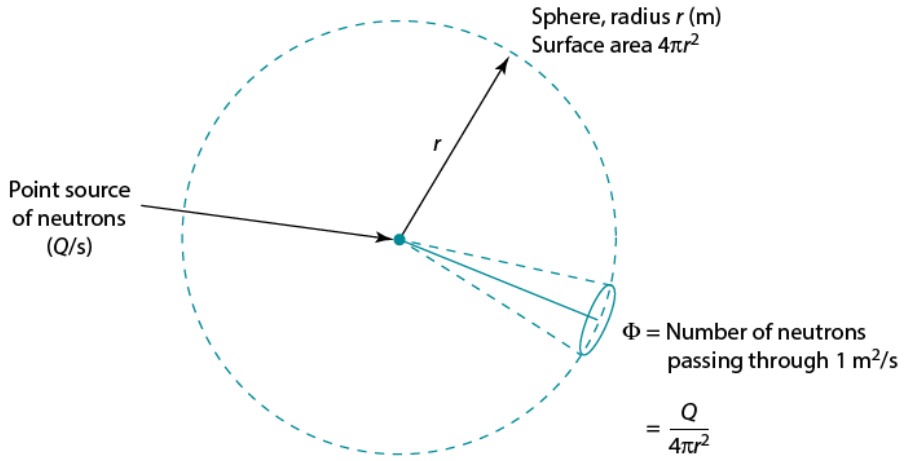


Figure 3.3 Flux from a point source.

EXAMPLE 3.4

Calculate the flux at a distance of 0.5 m from a source which emits 2×10^7 n/s.

$$\Phi = \frac{Q}{4\pi r^2}$$
$$= \frac{2\times10^7}{4\pi\times0.5\times0.5}$$
$$= 6.4\times10^6 \text{ n/m}^2/\text{s}$$

EXAMPLE 3.5

Calculate the γ photon flux at 1 m from a 0.1 TBq cobalt-60 source. (Cobalt-60 emits two γ rays per disintegration.) From Chapter 2, we know that 0.1 TBq = 10^{11} dps, but for ^{60}Co there are two γ photons per disintegration. Therefore

$$Q = 2\times10^{11} \text{ photons/s}$$
$$\Phi = \frac{Q}{4\pi r^2}$$
$$= \frac{2\times10^{11}}{4\pi\times1^2}$$
$$= 1.6\times10^{10} \ \gamma \text{ photons/m}^2/\text{s}$$

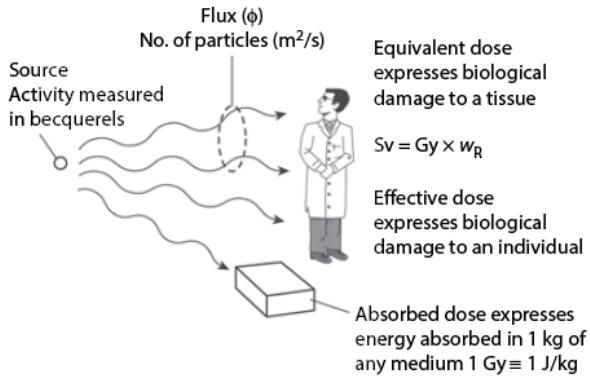


Figure 3.4 The relationship of units.

3.9 RELATIONSHIP OF UNITS

The relationship of the units which have now been introduced is illustrated in Figure 3.4. The gray describes an absorbed dose in any medium and the sievert expresses the biological effect on the human body. In radiation protection, it is clearly the biological effect of radiation that is of interest and so whenever possible an equivalent dose or effective dose should be used.

In everyday radiation protection, the term **dose** is often loosely used to mean either of the quantities **absorbed dose** or **equivalent dose**. In the following chapters, the term dose will generally be taken to mean either **equivalent dose** or **effective dose** depending on the context.

3.10 INTERNATIONAL RADIATION SYMBOLS

The long-established and internationally agreed upon symbol for ionizing radiation is the trefoil symbol

Figure 3.5 The international trefoil symbol for radiation (black on yellow).

Figure 3.6 The new symbol for very high-activity sources.

shown in Figure 3.5. This symbol is used on packages containing radioactive materials and as a warning sign at the entrance to areas where there is a significant radiological hazard.

In 2007, the International Atomic Energy Agency and the International Organization for Standardization introduced an additional symbol for use in the special situation where very high-activity radiation sources are in use (see Figure 3.6). The symbol is intended for use on the containers of very high-activity sources such as those in food irradiators, industrial radiography equipment and teletherapy equipment for cancer treatment (see Chapter 15, Section 15.2.6 and Chapter 16, Section 16.4). The new symbol should not be used on transport packages or at access points to radiation controlled areas.

SUMMARY OF KEY POINTS

- **Radiation:** Transfers energy from the source to the absorbing medium.
- **Ionization:** Removal of orbital electron – production of ion pairs.
- **Ionization chamber:** Application of electric field causes a current of ions to flow.
- **Absorbed dose:** Energy deposition in any medium by any type of ionizing radiation, 1 Gy = 1 J/kg.
- **Equivalent dose:** Obtained by multiplying the absorbed dose by the radiation weighting factor for the particular type of radiation; the equivalent dose from different types of radiation may then be added to give a measure of the overall biological effect; the unit is the sievert.
- **Radiation weighting factor, w_R:** Measure of the ability of a particular type of radiation to cause biological damage, which is related to the density of ionization. $w_R = 1$ for β, X and γ, 5 for protons, 2.5 for thermal neutrons, 2.5–20 for fast neutrons (dependent on energy) and 20 for α particles.
- **Effective dose:** An indicator of the detrimental effects of radiation on the body as a whole when different body tissues are exposed to different levels of equivalent dose; obtained by multiplying the equivalent dose to each exposed organ by its tissue weighting factor, w_T, and then summing over all of the exposed organs.
- **Tissue weighting factor, w_T:** A factor reflecting the radiosensitivity of a particular tissue or organ and its overall contribution to the detriment.
- **Dose** = Dose rate × Time.
- **Flux** from point source = $Q/(4\pi r^2)$.

CHAPTER 4
Biological effects of radiation

4.1 INTRODUCTION

Within weeks of Rontgen's announcement of the discovery of X-rays, workers in many countries were conducting experiments and exploring medical applications. However, by early 1896, there were reports that the radiation was affecting the health of workers in the field and a letter appeared in *Nature* describing the effects of repeated exposure of the hands to X-rays. Initially, the effects were confined to superficial skin damage and hair loss but, later, evidence was accumulating of more serious effects. One of the many tragic cases was that of Clarence Dally, who worked for Thomas Edison as a glassblower but in 1896 turned to the development and application of X-ray equipment. At this time, it was common practice to check that the machine was operating by placing the wrist within the beam area where a heating effect would be experienced. Within months, Dally was showing symptoms of skin damage and hair loss. Over a period of a few years the injuries to the left hand developed into a large ulcerative lesion (see Figure 4.1). Both arms were amputated in an attempt to prevent the spread of cancer but Dally died in 1904 at the age of 39.

By 1911, Hesse had studied the histories of 94 cases of tumours induced in man by X-rays, of which 50 cases were among radiologists. By 1922, it was estimated that more than 100 radiologists had died from radiation-induced cancer. Similarly, it has been estimated that the death rate from leukaemia among early radiologists was about nine times that among other physicians. Other studies have shown that the average life expectancy of the pioneer radiologists was reduced by approximately 2–3 years compared with physicians in general practice. These studies illustrated the early forms of damage produced by X-rays and gave some indication of the longer-term effects. They showed that for some types of damage, such as skin cancer, there is a latency period of between 10 and 30 years, and some radiologists observed malignant skin changes as late as 25 years after discontinuing fluoroscopic examinations.

In parallel with this experience with X-rays, scientists were also working with the newly discovered but naturally occurring radioactive materials. Both Henri Becquerel and Pierre Curie reported having suffered skin burns from carrying vials of radium in their pockets. Dramatic evidence of the effects of the ingestion of radium came from the radium dial painting industry which developed in the United States around 1917. This industry employed several thousand people, mainly young women, to paint luminous dials for watches and instruments (Figure 4.2). The paint consisted of a mixture of radium and a luminescent material which glows as a result of bombardment by the alpha particles from radioactive decay. The painters had the habit of 'pointing' their paintbrushes with their lips and, in doing so, ingested significant amounts of radium, typically a few megabecquerels (MBq). Within a few years the damaging effects were evident in the form of loss of teeth, anaemia, and necrosis and sarcoma of bone, particularly the jaw bone. It is not known how many radium dial painters actually died from the effects of radiation but it seems likely to have been some hundreds.

Other groups that suffered the effects of radiation were the miners at the Schneeberg cobalt mines of Saxony and at the Joachimsthal pitchblende mines of Bohemia. It had been known for some centuries that these miners suffered a very high incidence of lung cancer. After the discovery of radioactivity in 1896, it became clear that a large proportion of the cancer incidence was caused by radiation from daughter products of uranium which were present in high concentrations in the ore bodies.

During the second and third decades of the twentieth century, there were many cases of high exposure to radium, particularly from the use of radium as a therapeutic agent. It was administered for a large variety of diseases, ranging from arthritis to insanity, often with unfortunate consequences.

The largest population groups exposed to high levels of radiation are the atomic bomb survivors in Japan. Soon after the end of the war, a commission was set up, later to become the Radiation Effects Research Foundation, to study the long-term consequences. In its various studies, the health and survival of over 100,000 people have been followed, yielding information of great value in understanding and quantifying the long-term effects of radiation exposure.

On the basis of the aforementioned evidence, it is now understood that the interaction of ionizing radiation with the human body, arising either from external sources outside the body or from internal contamination of the body by radioactive substances, leads to biological effects which may later show up as clinical symptoms. The nature and severity of these symptoms and the time at which they appear depend on the amount of radiation absorbed and the rate at which it is received. In addition to the effects on the person receiving the dose, damage to the germ cells in the reproductive organs – the gonads – can result in heritable effects which arise in later generations.

4.2 BASIC HUMAN PHYSIOLOGY

Physiology is concerned with the functions of the body as a whole and the component organs and systems. Some basic knowledge of physiology is necessary for an understanding of the ways in which radioactivity can enter and become distributed in the body. Humans can be regarded as machines consisting of various interrelated systems, each performing some important function. The systems which are most relevant to an understanding of the behaviour of radioactive substances which enter the body are the circulatory, respiratory and digestive systems (see Figure 4.3).

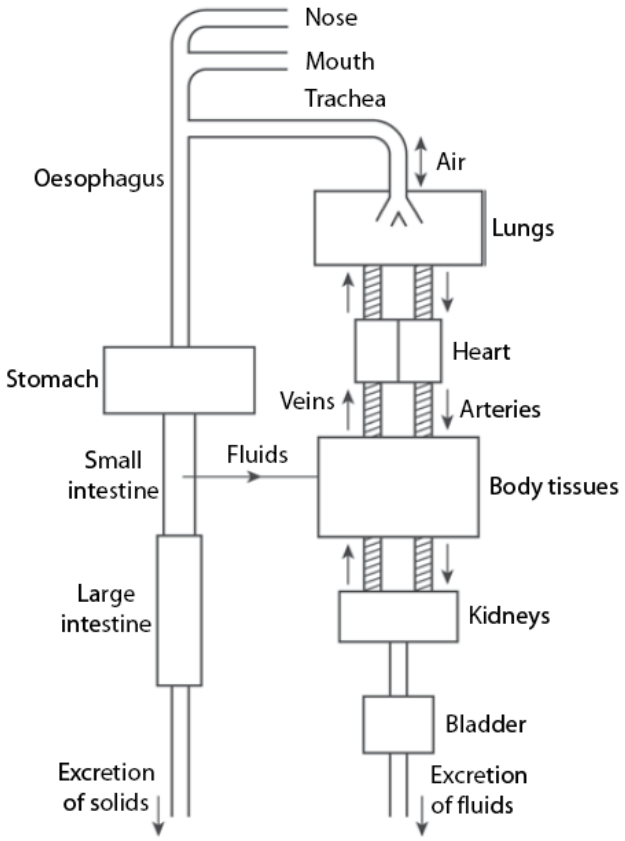


Figure 4.3 Schematic illustration of human physiology.

4.2.1 CIRCULATORY SYSTEM

The circulatory system is a closed circuit of tubes around which the blood is pumped by the action of the **heart**. Blood is the transport mechanism of the body and it circulates to almost every region carrying nutrients (from food) and oxygen to the cells. It also picks up waste products and carbon dioxide and transfers them to the excretory organs. The heart is actually two pumps: the left side pumps the blood through the **arteries** to the tissues. Nourishment is transferred from the tissues to the cells via the tissue fluid. The blood, after passing through the tissues, returns to the right side of the heart via the **veins**.

The blood is then pumped to the **lungs** where it becomes oxygenated before returning to the left side of the heart.

The blood in the arteries contains a lot of oxygen and is bright red in colour, whereas the blood returning from the tissues contains very little oxygen and is dark red with a bluish tinge. The body contains about 5 litres of blood which circulates about once a minute. There are three types of blood cells, each performing an essential function: **red cells** (erythrocytes), **white cells** (leukocytes) and **platelets** (thrombocytes). The function of the red cells is to transport the food and oxygen required by the body, whereas the white cells serve as a means of defence against infection by digesting microorganisms. Platelets play a vital role in the formation of clots at the site of injuries.

4.2.2 RESPIRATORY SYSTEM

Physiological respiration (or breathing) is the method by which oxygen is taken into the lungs and carbon dioxide eliminated. The oxygen is absorbed by the blood as it passes through the lungs and carried to the tissues as described earlier. The tissues produce carbon dioxide as a gaseous waste product and this is carried back by the blood to the lungs and breathed out. The volume of air breathed per day is approximately 20 m^3, of which half is usually considered to be breathed during the 8 h of work.

In the process of respiration, airborne contaminants, either in the form of gaseous or particulate materials (i.e. airborne dusts), are inhaled. Gases pass freely into the lungs and enter the bloodstream to a greater or lesser extent, depending on their solubility. In the case of particulate matter, only a fraction of the inhaled material is deposited in the lungs; the remainder is either exhaled or deposited in the upper respiratory passages and subsequently swallowed. The behaviour of the material deposited in the lungs depends mainly on its solubility. Highly soluble materials are absorbed rapidly into the bloodstream, perhaps in a matter of hours, whereas insoluble material may persist in the lungs for many months. Clearly, then, the respiratory system represents a route of entry for radioactive substances which can remain in the lungs for long periods or be transported by the bloodstream to other parts of the body.

4.2.3 DIGESTIVE SYSTEM

The digestive system consists of the oesophagus, the stomach and the small intestine, which in turn is connected to the large intestine. Food taken in by the mouth is converted into a form suitable for the production of heat and energy, and the molecules necessary for the growth and repair of tissues. The large molecules in the food are broken down by enzymes in the digestive tract before being absorbed into the bloodstream and passed via the liver to the tissues. The unabsorbed food, together with bacteria and cells shed from the intestine wall, is passed out as solid waste (faeces). Liquid waste (the waste products of cells dissolved in water) is excreted from the body via the kidneys and bladder as urine.

Soluble radioactive contamination, when swallowed, may pass through the walls of the digestive tract and become absorbed into the bloodstream, which carries it to all parts of the body. It is then likely to become concentrated mainly in some specific organ or tissue, which it will irradiate until it decays or is excreted. Insoluble contamination passes through the digestive tract and is excreted in the faeces. During its passage through the body it will irradiate the tract and the large intestine.

4.3 CELL BIOLOGY

All living creatures and organisms consist of tiny structures known as cells. The basic components of a cell are the **nucleus**, a surrounding liquid known as the **cytoplasm** and a **membrane** which forms the cell wall. Figure 4.4 shows a simplified representation of a 'typical' human cell.

The simplest picture of the cell is that the cytoplasm is the 'factory' of the cell, whereas the nucleus contains all the information which the cell needs to carry out its function and reproduce itself. Certain structures within the cytoplasm (organelles) break down food nutrients and convert them into energy and smaller molecules. These smaller molecules are later converted into complex molecules needed by the cell either for maintenance or duplication.

The nucleus contains chromosomes, which are tiny threadlike structures made up of genes. Human cells normally contain 46 chromosomes. The genes

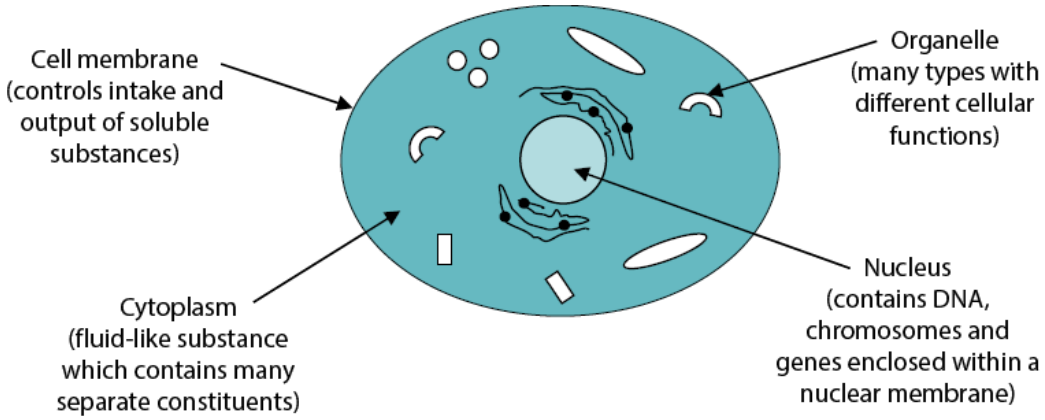


Figure 4.4 Structure of human cell (schematic).

consist of deoxyribonucleic acid (DNA) and protein molecules, and carry the information which determines the characteristics of the daughter cell.

Cells are able to reproduce to compensate for cells that die. The life of different types of human cells, and hence the rate of reproduction, varies from a few hours to many years. Reproduction of cells occurs in two ways, known as **mitosis** and **meiosis**. The mitotic cells are the ordinary cells in the body and in mitosis the chromosomes duplicate by splitting lengthways. The original cell then divides into two new cells, each identical to the original cell.

Meiosis is a special kind of division which occurs during the formation of the sexual reproduction cells, namely the sperm in the male and the ovum in the female. It occurs only once in the cell's life cycle and only in the reproductive cells. In sexual reproduction a sperm and an ovum unite and the chromosomes combine to form a new cell containing genetic material (i.e. genes) from each of the parents. The embryo and subsequently the offspring develop from this single cell (the fertilized ovum).

4.4 INTERACTION OF RADIATION WITH CELLS

The basic difference between nuclear radiations and the more commonly encountered radiations such as heat and light is that the former have sufficient energy to cause ionization. In water, of which cells are largely composed, ionization can lead to molecular changes and to the formation of chemical species of a type that is damaging to the chromosome material. The damage takes the form of changes in the construction and function of the cell. In the human body, these changes may manifest themselves as clinical symptoms such as radiation sickness, cataracts or, in the longer term, cancer.

This overall process is usually considered to occur in four stages, as follows:

1. **The initial physical stage**, lasting only an extremely small fraction (c. 10^{-16}) of a second in which energy is deposited in the cell and causes ionization. In water the process may be written as

$$H_2O \xrightarrow{\text{radiation}} H_2O^+ + e^-$$

   where H_2O^+ is the positive ion and e^- is the negative ion.
2. **The physicochemical stage**, lasting about 10^{-6} s, in which the ions interact with other water molecules resulting in a number of new products. For example, the positive ion dissociates:

$$H_2O^+ \longrightarrow H^+ + OH$$

   The negative ion, that is the electron, attaches to a neutral water molecule which then dissociates:

$$H_2O + e^- \longrightarrow H_2O^-$$

$$H_2O^- \longrightarrow H + OH^-$$

Thus the products of the reactions are H^+, OH^-, H and OH. The first two ions, which are present to quite a large extent in ordinary water, take no part in subsequent reactions. The other two products, H and OH, are called **free radicals**, that is they have an unpaired electron and are chemically highly reactive. Another reaction product is hydrogen peroxide, H_2O_2, which is a strong oxidizing agent and is formed by the reaction

$$OH + OH \longrightarrow H_2O_2$$

3. **The chemical stage**, lasting a few seconds, in which the reaction products interact with the important organic molecules of the cell. The free radicals and oxidizing agents may attack the complex molecules which form the chromosomes. They may, for example, attach themselves to a molecule or cause links in long chain molecules to be broken.
4. **The biological stage**, in which the time scale varies from tens of minutes to tens of years depending on the particular symptoms. The chemical changes discussed earlier can affect an individual cell in a number of ways. For example, they may result in

   a. the early death of the cell or the prevention or delay of cell division; or
   b. a permanent modification which is passed on to daughter cells.

The effects of radiation on the human body as a whole arise from damage to individual cells, but the two types of changes have quite different results. In the first case, the death or prevention of division of cells results in the depletion of the cell population within organs of the body. Below a certain level of dose (a threshold), the proportion of cells damaged will not be sufficient to affect the function of the organ and there will be no observable effect on the organ or the body as a whole. Above the threshold, effects will start to be observed and the severity of the effects will increase quite rapidly as the dose increases. This means that within the range of variability between individuals, the relationship between the dose and the severity of the effects can be assessed with reasonable confidence. This type of effect was formerly referred to as **deterministic** but the International Commission on Radiological Protection (ICRP) has now adopted the more descriptive term **harmful tissue reaction**.

In the second case, modification of even a single cell may result, after a latency period, in a cancer in the exposed individual or, if the modification is to a reproductive cell, the damage may be transmitted to later generations and give rise to **heritable** effects. In these cases, it is the likelihood of the effect occurring that depends on the dose. This type of effect is referred to as **stochastic**, meaning 'of a random or statistical nature'.

To summarize, radiation-induced changes at the cellular level can lead to two distinct types of injury:

- **Harmful tissue reactions** in which, above a certain threshold dose, the severity of the effects increase with increasing dose. These effects are discussed in Section 4.5.
- **Stochastic effects**, in which the probability of occurrence of the effect increases with dose. The effects include cancer induction (see Section 4.6) and heritable effects in future generations (see Section 4.7).

4.5 HARMFUL TISSUE REACTIONS

4.5.1 ACUTE RADIATION EFFECTS

The harmful tissue reactions that arise from acute radiation exposure (a large dose over a relatively short period of time) are those that occur within a few weeks after the receipt of the dose. The effects result from a major depletion of cell populations in a number of body organs caused by cell-killing and the prevention or delay of cell division. The main effects are attributable to bone marrow, gastrointestinal or neuromuscular damage, depending on the dose received. Acute absorbed doses above about 1 Gy give rise to nausea and vomiting. This is known as radiation sickness and it occurs a few hours after exposure as a result of damage to cells lining the intestine. Absorbed doses above about 3 Gy can lead to death, probably 10 to 15 days after exposure.

There is no well-defined threshold dose below which there is no risk of death from acute doses, although below about 1.5 Gy the risk of early death would be very low. Similarly, there is no well-defined point above which death is certain, but the chances of surviving an acute dose of about 8 Gy would be very low. A reasonable estimate can be made of the dose which would be lethal for 50% of the exposed subjects within 60 days of exposure. This is called LD_{50}^{60} and is thought to have a value of between 3 and 5 Gy for man. For doses up to about 10 Gy, death is usually caused by secondary infections that result from depletion of the white blood cells that normally provide protection against infection. The range of doses from 3 to 10 Gy is often called the region of **infection death**. In this range the chances of survival can be increased by special medical treatments, which include isolating the subject in a sterile (i.e. infection-free) environment and giving a bone marrow transfusion to stimulate white blood cell production.

For doses above about 10 Gy survival time drops abruptly to between 3 and 5 days. It remains at about this figure until much higher doses are reached. In this region the radiation dose causes severe depletion of the cells lining the intestine. Gross damage occurs in the lining of the intestine, followed by severe bacterial invasion. This is called the region of **gastrointestinal death**.

At much higher doses, survival times become progressively shorter. There are very few human data in this region but, from animal experiments, the symptoms indicate some damage to the central nervous system; hence, the region is called the region of **central nervous system death**. However, it is found that death is not instantaneous even in animals irradiated with doses in excess of 500 Gy.

Another effect which shows up soon after an acute over-exposure to radiation is **erythema**, which is reddening of the skin. In many situations the skin is subject to more radiation exposure than most other tissues. This is especially true for β rays and low-energy X-rays. A dose of about 3 Gy of low-energy X-rays will result in erythema, and larger exposures may lead to other symptoms such as changes in pigmentation, blistering and ulceration.

The levels of exposure of workers and members of the public arising from normal operations in the nuclear energy industry, or from industrial and medical applications of radiation, are far below the levels that would induce early effects. Such high doses could only be received in the unlikely event of an accident. However, the low doses received in normal operations may cause harmful effects in the long term and these are discussed later.

It will have been noted that in this discussion, early effects have been considered in terms of the absorbed dose, expressed in gray (Gy), rather than as equivalent dose in sievert (Sv). This is really a question of definition; the radiation weighting factor, w_R, discussed in the previous chapter, and hence the concept of equivalent dose, is intended to apply only to exposures within the normal recommended limits (see Chapter 6) and should not be applied to doses at levels which could lead to early effects.

4.5.2 LATE TISSUE REACTIONS

Another radiation effect which may be described as a tissue reaction but which may not occur for many years is damage to the lens of the eye. This takes the form of observable opacities in the lens or, in extreme cases, visual impairment as the result of a cataract. The ICRP has undertaken a review of the evidence and now considers that the threshold dose for effects on the lens of the eye is an absorbed dose of 0.5 Gy. The dose limit for the lens of the eye (see Chapter 6, Section 6.3) is set at such a level as to avoid adverse effects.

There is some evidence from animal experiments that exposure to radiation may slightly reduce the life expectation of individuals who do not exhibit any specific radiation-induced symptoms. Observations of human populations exposed at relatively high levels indicate that if life-shortening occurs at all, it is very slight, almost certainly less than 1 year per sievert.

4.6 STOCHASTIC EFFECTS: CANCER INDUCTION

It became apparent in the early part of the twentieth century that groups of people such as radiologists and their patients who were exposed to relatively

high levels of radiation showed a higher incidence of certain types of cancer than groups not exposed to radiation. More recently, detailed studies of the populations exposed to radiation from atomic bombs, of patients exposed to radiation therapy and of groups exposed occupationally, particularly uranium miners, have confirmed the ability of radiation to induce cancer.

Cancer is an over-proliferation of cells in a body organ. It is thought that cancer may result from damage to the control system of a single cell, causing it to divide more rapidly than a normal cell. The defect is transmitted to the daughter cells so the population of abnormal cells builds up to the detriment of the normal cells in the organ. The estimation of the increased risk of cancer is complicated by the long and variable latent period, from about 5 to 30 years or more, between exposure and the appearance of the cancer, and by the fact that radiation-induced cancers are not normally distinguishable from those that arise spontaneously or as a result of other carcinogens such as tobacco smoke. The incidence of cancer in a normal population is high, with about one person in three expected to die eventually from some form of cancer. This high background makes it very difficult to establish whether any additional cases of a particular type of cancer are the result of radiation exposure, even in populations that have been exposed at relatively high levels.

At the high doses and dose rates experienced by the groups mentioned earlier, the ICRP has estimated that, averaged over a typical population of all ages, a dose of 1 Sv to each individual would result in a radiation-induced fatal cancer in about 10% of the persons exposed. This is the same as saying that the average risk to an individual from a dose of 1 Sv is about 1 in 10 or 0.1. The extrapolation of this estimate to the much lower doses and dose rates normally encountered as a result of operations in the nuclear industry and elsewhere introduces further uncertainty. A very conservative approach would be to make a linear extrapolation from high to low dose. Since a dose of 1 Sv carries a risk of fatal cancer of 0.1, the risk from a dose of 1 mSv would be 1000 times lower, or 0.0001. However, on the basis of theoretical considerations, experiments on animals and other organisms, and limited human data, ICRP concluded that this is likely to overestimate the risks of radiation exposure at low doses and dose rates by a factor of between 2 and 10. This factor is referred to as the **dose and dose rate effectiveness factor (DDREF)** and, to err on the safe side, ICRP recommends using only the factor of 2. This means that the additional risk of fatal cancer imposed on an average individual by exposure to radiation at low doses and dose rates can be estimated using a **risk coefficient** of 0.05 per Sv (this can be written as 5×10^{-2} per Sv). Using this coefficient, the risk of fatal cancer due to a given dose can be estimated using the relationship

$$\text{Risk} = \text{Dose (Sv)} \times \text{Risk coefficient (Sv}^{-1}\text{)}$$

For a dose of 10 mSv (0.01 Sv), the risk of fatal cancer would be

$$\text{Risk} = 0.01 \text{ Sv} \times 5 \times 10^{-2} \text{ per Sv} = 5 \times 10^{-4}$$

In addition to fatal cancers, exposure to radiation also gives rise to cancers which are non-fatal or curable. These need to be taken into account, but it would clearly be inappropriate to give them the same weight as fatal cancers. Recognizing this, ICRP has developed the concept of **detriment** that allows effects of different importance to be combined to give an overall measure of the detrimental effects of radiation exposure. This is discussed further in Section 4.8.

4.7 STOCHASTIC EFFECTS: HERITABLE

The heritable effects of radiation result from damage to the reproductive cells. This damage takes the form of alterations, known as **genetic mutations**, in the hereditary material of the cell.

It has already been mentioned that reproduction occurs when the ovum is fertilized by a sperm. As a result, the offspring receives a complete set of genetic material from each parent. Thus the child receives two complementary sets of genes, one from each of its parents. In general it is found that one gene is 'dominant' and the other 'recessive'. The dominant gene determines the particular characteristic with which it is associated.

SUMMARY OF KEY POINTS

- **Biological effects of radiation:** Became apparent very soon after the discoveries of Rontgen and the Curies.
- **Early workers in field:** Radiation effects observed in various exposed groups, including radiologists, dial painters and miners.
- **General population:** Largest exposed groups were bomb survivors. Follow-up studies have provided valuable information on long-term effects.
- **Physiology:** The study of the functions of the body as a whole and its component organs and systems.
- **Heart:** Pumps blood to all parts of the body via the arteries and the veins.
- **Blood:** Carries food nutrients and oxygen to cells and removes waste products.
- **Red blood cells:** Transport food and oxygen.
- **White blood cells:** Defend the body against infection.
- **Platelets:** Vital to the formation of clots.
- **Respiration:** Method by which oxygen is taken into the lungs and carbon dioxide eliminated.
- **Digestive system:** Converts food into a form suitable for the production of heat and energy, and molecules necessary for the growth and repair of tissues.
- **Stages of radiation damage process:**
  1. Initial physical stage (c. 10^{-16} s) consisting of ionization and excitation of atoms and molecules.
  2. Physicochemical stage (10^{-8}–10^{-5} s) consisting of dissociation of ions and formation of free radicals.
  3. Chemical stage (a few seconds) consisting of the interaction of free radicals with other molecules in the body.
  4. Biological stage (minutes to years) in which the chemical reactions show up as effects in individual cells.
- **Components of cell:** Nucleus, cytoplasm and outer membrane.
- **Nucleus:** Contains chromosomes which are threadlike structures made up of genes.
- **Genes:** Carry the information which determines the characteristics of daughter cells.
- **Mitosis:** Process by which single cells reproduce.
- **Meiosis:** A stage in the formation of the reproductive cells – the sperm in the male and the ovum in the female.
- **Effects of radiation on cells:** Inhibition of mitosis, chromosome aberrations.
- **Acute effects:** Effects occurring within a few weeks of a very large exposure; due to depletion of cell populations.
- **Late effects:** Effects occurring at later times, typically some years after exposure; main effect is cancer induction.
- **Heritable effects:** May appear in descendants of exposed individuals.
- **Stochastic effects:** Probability of occurrence depends on dose; mainly cancer and genetic effects.
- **Harmful tissue reactions:** Effects in tissues, the severity of which increases with dose, and for which a threshold may apply; mainly the early radiation effects plus certain late effects, such as cataract formation, formerly known as deterministic effects.
- **Detriment:** The harm from exposure to radiation, based on the probability of a stochastic effect weighted for lethality and life impairment.
- **Risk coefficient:** The probability of a stochastic effect from a dose of 1 Sv. When the probability is weighted for the severity of the effect it becomes a nominal risk coefficient.

CHAPTER 5
Natural and man-made radiation

5.1 INTRODUCTION

Throughout history, man has been exposed to radiation from the environment. This natural background radiation comes from two main sources: cosmic radiation and 'primordial' radiation from terrestrial sources. Note that both of these sources can lead to radioactivity within the body.

It is not clear whether the natural background radiation has been harmful or beneficial to the development of the human species. It was pointed out in the previous chapter that a very small, but finite, fraction of the natural mutations in cells must be beneficial since they have contributed to the evolution of higher forms of life. Conversely, some genetic mutations lead to hereditary defects that may result in death. It appears that these two effects have achieved some sort of balance and that life has evolved to its present state despite background radiation, or perhaps even because of it.

In addition to the natural sources of background radiation, many artificial sources of radiation have been introduced since the discovery of X-rays and radioactivity at the end of the nineteenth century, and particularly since the exploitation of the process of nuclear fission in the middle of the twentieth century. These artificial sources now add a significant contribution to the total radiation exposure of the population.

5.2 COSMIC RADIATION

Cosmic radiation reaches the Earth mainly from the Sun but also from interstellar space. It is composed of a very wide range of penetrating radiations which undergo many types of reactions with the elements they encounter in the atmosphere. The atmosphere acts as a shield and significantly reduces the amount of cosmic radiation that reaches the Earth's surface. This filtering action means that the dose rate at sea level is less than at higher altitudes. For example, the mean dose rate from cosmic radiation at sea level at the equator is about 0.2 mSv/y, while the dose rate at an altitude of 3000 m is about 1 mSv/y. The average dose rate in the United Kingdom from cosmic radiation is about 0.33 mSv/year.

One very important radionuclide arises mainly from the interaction of neutrons in cosmic radiation with nitrogen in the upper atmosphere to form carbon-14 (C-14) as follows:

$$^{14}N\ (n, p)\ ^{14}C$$

C-14, which has a half-life of 5715 years, diffuses to the lower atmosphere, where it may become incorporated in living matter. Similarly, small concentrations of other less important radionuclides such as tritium (H-3, half-life 12.32 y), chlorine-36 (Cl-36, half-life 3.01×10^5 y) and calcium-41 (Ca-41, half-life 1.03×10^5 y) are maintained in the lower atmosphere by cosmic ray reactions. Some of these radioisotopes, particularly C-14, can be absorbed by plant life and subsequently cycled into the whole food chain.

5.3 RADIATION FROM TERRESTRIAL SOURCES

The rocks and soil of the Earth's strata contain small quantities of the radioactive elements uranium and

thorium and their daughter products. The concentration of these elements varies considerably depending on the type of rock formation. In sandstone and limestone regions the concentration is much lower than in granite. Thus the dose rate depends on the geographic location. In the United Kingdom, the average effective dose of γ radiation from this source is about 0.35 mSv/y. In some areas, the dose rate may be several times higher than this value.

These primordial radioisotopes are also present in low concentrations in building materials, such as stone and brick used in construction, and can lead to a further contribution to natural background radiation dose.

5.4 NATURALLY OCCURRING RADIOACTIVE MATERIAL (NORM)

The presence of naturally occurring radioactivity in rocks and soil also means that most natural materials are slightly radioactive. Usually the resulting radiation exposure is trivial, but there are materials that can cause significant exposure, either because they contain higher levels of naturally occurring radioactivity or because they are processed or used in such a way as to enhance the exposure. These materials are known as **NORM** (naturally occurring radioactive materials). NORM that have been concentrated or exposed to the accessible environment as a result of human activities such as manufacturing, mineral extraction or materials processing is known as technologically enhanced NORM or **TENORM**. Where substances are processed, the concentrations of the radioactivity can be increased in some of the process streams and give rise to the exposure of workers in the processing plant. In other cases, the products of processing, such as consumer products or building materials, can contain enhanced levels of radioactivity and result in an increased radiation exposure of the general population.

In the oil and gas industries, naturally occurring radium and its daughter products can build up as scale in pipes and vessels. The descaling of these results in occupational radiation exposure and in waste streams containing radium.

In the smelting of iron ore, high concentrations of lead-210 (Pb-210) and polonium-210 (Po-210) occur in dusts and residues. In other metal smelting applications, the use of special mineral sands containing natural uranium and thorium can lead to exposures either directly or from the enhanced concentrations in foundry slag. Another material containing levels of uranium, thorium and potassium-40 (K-40) (also a primordial radioisotope) that can be of radiological significance is phosphate rock. This is often used as an agricultural fertilizer. In addition, gypsum, which arises as a by-product of phosphate processing, is widely used in building materials.

It is the responsibility of enterprises that extract, process or use NORM to establish by appropriate surveys and assessments whether the doses are likely to be of radiological significance and, where necessary, to introduce adequate measures to ensure that exposures are kept as low as reasonably practicable.

5.5 RADIOACTIVITY IN THE BODY

The ingestion and inhalation of naturally occurring radionuclides gives rise to a dose which varies considerably depending on the location, diet and habits of the individual concerned. K-40 and nuclides from the uranium and thorium series contribute most to this dose, with a minor contribution from C-14.

Naturally occurring radioactivity is also taken up by plants and animals, with the result that most foodstuffs contain measurable amounts of natural radioactivity. Of ordinary foods, cereals have a relatively high radioactive content, whereas milk, produce, fruit and vegetables have a low content. The intake of natural radioactivity varies greatly with diet and with location. The average dose in the United Kingdom from this source is about 0.25 mSv/y.

However, by far the biggest contribution to the radioactivity taken into the body comes from the inhalation of the gaseous decay products of the uranium and thorium radioactive series, namely radon, thoron and their daughters.

5.5.1 RADON

Radon is a colourless and odourless gas formed from the radioactive decay of the tiny amounts of

natural uranium and thorium in rocks, soils and many building materials. The most important isotope is Rn-222, which is a member of the uranium series but, in some circumstances, Rn-220 (sometimes called thoron because it comes from the thorium series) can be of some significance. Radon diffuses from the ground and from building structures to give a measurable concentration in the atmosphere in the open air and, particularly, within buildings. This concentration varies significantly with geographical location depending upon the uranium content of the underlying geology. In the open air, concentrations are generally low and do not represent a significant radiological problem. Higher concentrations occur within buildings, partly as a result of diffusion from the structural materials but also because radon from the ground can enter the building. The atmospheric pressure indoors is often slightly lower than that outside, especially in the winter months, and radon gas from the ground can be drawn into the building through cracks in the floor, shrinkage gaps between the floor and the walls, as well as any service ducts. In addition, being much heavier than air, radon tends to accumulate in cellars and basements. The other major factor is the restricted ventilation within buildings. It should be noted that radon dissolves readily in water and therefore it can also be found in some natural spring or mineral waters.

Radon is the single largest contributor to background radiation dose (see Figure 5.1). The radioactive daughter products of radon attach to dust particles that, when inhaled, irradiate the lungs and increase the risk of lung cancer. The damage is caused by α radiation, which, despite its small range, harms cells in the sensitive lining of the lungs. Studies in the United Kingdom suggest that radon is responsible for 3%–5% of all lung cancers and, according to the US Environmental Protection Agency, radon is the second most frequent cause of lung cancer, after cigarette smoking, and causes 21,000 lung cancer deaths per year in the United States.

The average annual dose to members of the UK population from this source is about 1.3 mSv/y, but studies have shown that in some dwellings, in 'radon-affected' areas, the dose rate can be up to 100 times the average. As a result, there are programmes in a number of countries to identify dwellings and workplaces that have high concentrations and, where necessary, to undertake remedial work.

Radon can be 'actively' measured using specialized ionization chambers which continuously measure and record the amount of radon or its decay products in the air. However, such equipment is expensive and requires expert operation. As radon concentrations inside buildings can vary significantly with time, depending on area usage and weather conditions, prolonged measurements using

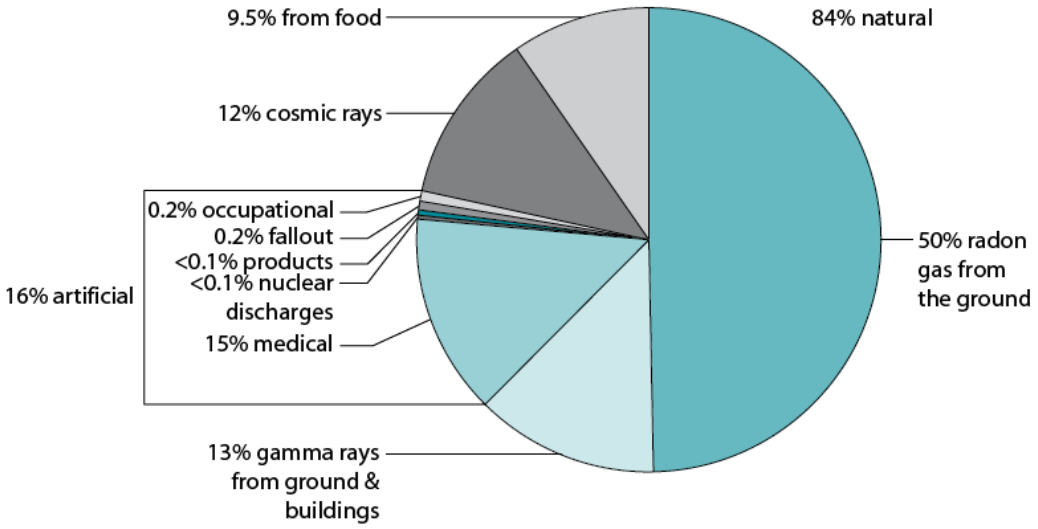


Figure 5.1 Breakdown of the per caput dose to the UK population in 2010 by source of exposure. (From Public Health England. 2016. *Ionising Radiation Exposure of the UK Population: 2010 Review*. PHE-CRCE-026, © Crown copyright 2016, *https://www.phe-protectionservices.org.uk/cms/assets/gfx/content/resource_3595csc0e8517b1f.pdf*.)

Figure 5.2 Passive radon detector. (Adapted with kind permission from Report HPA-RRP-001, *Ionising Radiation Exposure of the UK Population: 2005 Review*, by S. J. Watson et al., 2005, © Health Protection Agency.)

'passive' radon meters often provide a more reliable and much simpler approach. A typical passive radon detector is shown in Figure 5.2, and these devices are usually placed within buildings for a 3-month period. The detector contains a sensitive plastic that registers damage tracks when exposed to α particles. The tracks can then be counted under a microscope and used to give the average radon level during the 3-month period of the measurement.

In the United Kingdom, it is recommended that an activity concentration of radon in excess of 200 Bq/m^3 (averaged over one year) in the home would necessitate some action to reduce radon, whereas in the workplace a concentration of greater than the national radon reference level – annual average of 300 Bq/m^3 – requires notification to the regulatory authority (in this case the Health and Safety Executive) and remedial action to reduce radon concentration levels.

The simplest approach used to reduce ingress of the radon is by sealing walls and floors and increasing the ventilation. However, in some cases it may be necessary to fit a 'radon sump' to vent the gas into the atmosphere outside the building. A sump has a pipe connecting a space under a solid floor to the outside, and a small electric fan in the pipe continually sucks the radon from under the building and expels it harmlessly to the atmosphere.

More detailed information on radon and measures to mitigate its impact can be found at the following link: *http://www.ukradon.org/*.

Table 5.1 Typical average annual doses from natural radiation

Source	Dose (mSv/y)
Local γ radiation	0.35
Radon, thoron and decay products	1.30
Cosmic radiation	0.33
Intake of natural radioactivity	0.27
Total	~2.25

Source: Public Health England. 2016. *Ionising Radiation Exposure of the UK Population: 2010 Review*. PHE-CRCE-026.

5.6 SUMMARY OF DOSES FROM NATURAL RADIATION

Table 5.1 gives a list of the typical average annual doses from natural radiation in the United Kingdom. Local γ radiation comes from the U-238 and Th-232 series and from K-40. In certain parts of the world, it is much higher than the value given in Table 5.1. For example, in the monazite sand regions of India and Brazil, the annual whole-body doses from local γ radiation can be as high as 120 mSv/y.

As mentioned earlier, exposure to cosmic radiation is quite low at ground level but increases with altitude. The annual dose to an aircrew can be as much as 6 mSv.

5.7 MAN-MADE RADIATION EXPOSURE

In addition to the ever-present natural background radiation, there are several other sources of human exposure that have arisen only over the last 100 years or less. These are diagnostic radiology, radiotherapy, use of radioisotopes in medicine (a discipline known as nuclear medicine), radioactive waste, fallout from nuclear weapon tests and occupational exposures to radiation.

5.7.1 DIAGNOSTIC RADIOLOGY

It has been estimated that over 90% of the total exposure of the population from man-made sources of ionizing radiation comes from the diagnostic use

of X-rays. The most important regions of the body in this context are the bone marrow, the colon, the gonads and the fetus. The bone marrow is the site of the primitive blood-forming cells, and so irradiation of this region can lead to the induction of leukaemia. In the colon, there is rapid cellular regeneration within the intestinal epithelium, which is particularly sensitive to radiation damage. Irradiation of the gonads is important because of the possibility of heritable damage, although recent studies suggest that gonads are far less radiosensitive than previously thought. Irradiation of pregnant women has to be controlled very strictly in order to limit the possibility of physical or mental damage to the unborn child. The dose to the fetus varies widely depending on the radiological examination being performed. For example, a dental X-ray of a pregnant patient might lead to a fetal dose of <1 μSv, whereas a pelvic computerized tomography (CT) scan might result in approximately 15 mSv to the unborn child.

5.7.2 RADIOTHERAPY

The doses received by patients from radiotherapy, typically a few tens of grays (Gy), are very much larger than those typically delivered in diagnostic radiography. However, the number of people that undergo treatment by radiotherapy is much lower than the number having diagnostic procedures and so the average dose to the population from radiotherapy is much less than that from diagnostic radiology.

5.7.3 NUCLEAR MEDICINE

Radioisotopes are used in medicine to give a means of tracing the path and location of specific chemicals in the body. Since radioactive isotopes are chemically identical to stable isotopes of the same element, they will follow the same path and be concentrated to the same degree as the non-active isotopes in the body. Using suitable detectors (e.g. so-called gamma cameras), the behaviour of the active, and hence by analogy of the ordinary non-active, isotopes of the element may be determined. At much higher concentrations, unsealed radioisotopes can be used for therapeutic purposes (see Chapter 16, Section 16.5).

5.7.4 RADIOACTIVE WASTE

The increasing use of radioisotopes and, more particularly, the development of the nuclear power industry results in an ever-growing quantity of radioactive waste. Continued dispersal of low levels of radioactive waste to the environment means that members of the general population receive radiation exposure from this source. For this reason, very strict control is exercised over the release of radioactive waste to the environment (see Chapter 14). At present the contribution to the average exposure of members of the population from waste disposal is very low, <1 μSv/y.

5.7.5 ATMOSPHERIC FALLOUT

After the Second World War, several countries undertook atmospheric testing of nuclear weapons. Much of the radioactivity generated by the detonations was injected into the stratosphere (at altitudes of 10–20 km) and distributed around the world by the atmospheric circulation, gradually falling out of the atmosphere onto the surface of the Earth over a period of some years. This gives rise to radiation exposure of the population, mainly through contamination of foodstuffs. The nuclides of concern in radioactive fallout from nuclear weapons testing are similar to those arising from the operation of nuclear power stations. The two most important radionuclides are strontium-90 (Sr-90, half-life 28.8 y) and caesium-137 (Cs-137, half-life 30.2 y). Sr-90 concentrates in the skeleton and Cs-137 is distributed uniformly throughout the body. Although atmospheric testing largely ceased in the 1960s, traces of these radionuclides are still measurable 50 years later because of their relatively long half-lives.

Another source of atmospheric fallout is radioactivity released into the environment as a result of nuclear accidents, much the largest of which occurred at Chernobyl in the Ukraine in 1986. This and other accidents are discussed further in Chapter 17.

5.7.6 OCCUPATIONAL EXPOSURE

The dose from all occupational exposure, mainly in medicine, industry and research, is very small when averaged over the whole population. The estimated contribution to the average dose in the

United Kingdom is about 0.4 μSv/y mainly from the exposure of workers in the nuclear and medical sectors.

5.8 SUMMARY OF CURRENT SOURCES OF RADIATION

Table 5.2 lists the average annual doses received by members of the public in the United Kingdom from the current sources of man-made (often called 'anthropogenic') radiation.

Table 5.2 Average annual doses from man-made radiation in the United Kingdom

Source	Dose (mSv/y)
Diagnostic radiology	0.43
Radiotherapy	0.01
Radioactive waste[a]	0.0008
Fallout from nuclear weapons	0.005
Occupationally exposed persons	0.0004
Approximate total	0.45

Source: Public Health England, 2016, *Ionising Radiation Exposure of the UK Population: 2010 Review*, PHE-CRCE-026.

[a] Includes exposure to radionuclides routinely discharged or accidentally released into the environment.

SUMMARY OF KEY POINTS

- **Sources of background radiation**
- **Natural sources of radiation:**
  - *Cosmic radiation* originating from the sun and interstellar space. The atmosphere provides shielding.
  - *Radiation from uranium and thorium* with their daughter products in the Earth's crust.
  - *Naturally occurring radioactive material (NORM).* Material containing enhanced levels of natural radioactivity and which may need protection measures.
  - *Radioactivity in the body.* Mainly uranium and thorium plus daughters, and K-40.
  - *Radon.* Gaseous decay product of uranium and thorium. Inhalation of its daughter products is responsible for about half the average exposure to the population.
- **Man-made sources of radiation:**
  - *Medical uses of radiation and radioisotopes* for diagnostic and therapeutic purposes.
  - *Radioactivity in the environment* resulting from discharges of radioactive waste, fallout from weapons testing and nuclear accidents.
  - *Occupational exposure* from working with nuclear reactors, and from medical, dental, educational, veterinary, industrial and military applications.

CHAPTER 6
The external radiation hazard

8.1 SOURCE OF THE HAZARD

The **external radiation hazard** arises from sources of radiation outside the body. When radioactive material actually gets inside the body, it gives rise to an **internal radiation hazard**, which requires quite different methods of control. The internal radiation hazard is discussed in Chapter 9.

The external hazard may be from β, X, γ or neutron radiation, all of which can penetrate to the sensitive organs of the body. Alpha radiation is not normally regarded as an external radiation hazard, as it cannot penetrate the outer layers of the skin. The external hazard is controlled by applying the three principles of time, distance and shielding.

8.2 TIME

The dose accumulated by a person working in an area with a particular dose rate is directly proportional to the amount of **time** they spend in the area. The dose can thus be controlled by limiting the time spent in the area, as defined by the equation

$$\text{Dose} = \text{Dose rate} \times \text{Time}$$

EXAMPLE 8.1

The annual dose limit for workers is 20 mSv which, assuming a 50-week working year, corresponds to 0.4 mSv, or 400 μSv/week. How many hours can a worker spend each week in an area in which the dose rate is 20 μSv/h?

$$\text{Dose} = \text{Dose rate} \times \text{Time}$$
$$400 = 20 \times t$$
$$\therefore t = 20\ \text{h}$$

EXAMPLE 8.2

If a worker has to spend a full 40-hour work week in a particular area, what is the maximum dose rate which can be allowed?

$$\text{Dose} = \text{Dose rate} \times \text{Time}$$
$$400 = \text{Dose rate} \times 40$$
$$\therefore \text{Dose rate} = 10\ \mu\text{Sv/h}$$

EXAMPLE 8.3

What would be the annual dose to a worker who spends a full working year (say 2000 h) in an area where the average dose rate is 2.5 μSv/h?

$$\text{Dose} = \text{Dose rate} \times \text{Time}$$
$$= 2.5 \times 2000$$
$$= 5000\ \mu\text{Sv (or 5 mSv)}$$

EXAMPLE 8.4

The dose limit for individual members of the public is 1 mSv/y. What is the maximum dose rate permitted in an area that could be continuously occupied (i.e. 168 h/week) by members of the public? (Answer: ~0.11 μSv/h)

From Examples 8.1 to 8.4 it can be seen that the dose rates that are of particular interest and that are commonly encountered in and around facilities such as nuclear reactors range from about 0.1 μSv/h up to a few tens of μSv/h. However, it should not be inferred from the examples that the only requirement is that the dose should be less than the dose limit. As discussed in Chapter 6, Section 6.2, it is required that, within the limits, doses are as low as reasonably achievable (ALARA). This involves analyzing the situation to see if the sources of exposure or the time spent by workers in the area can be reduced. It also requires that means of reducing the dose rate need to be considered. The available methods are to increase the distance between the worker and the source of radiation, or to introduce some shielding material between the worker and the radiation source.

8.3 DISTANCE

8.3.1 A POINT SOURCE

Consider a point source of radiation which is emitting uniformly in all directions. It was shown in Chapter 3, Section 3.8 that the flux at a distance r from a point source is inversely proportional to the square of the distance r. This is due to the flux being evenly distributed over the surface area of a sphere of radius r. Since the radiation dose rate is directly related to flux, it follows that the dose rate also obeys the inverse square law. It should be noted that this is strictly true only for a point source, a point detector and negligible absorption of radiation between source and detector. The inverse square law may be written:

$$D \propto 1/r^2 \text{ or } D = k/r^2$$
$$\therefore Dr^2 = k$$

where k is a constant for a particular source.

$$\therefore D_1 r_1^2 = D_2 r_2^2$$

where D_1 is the dose rate at distance r_1 from the source and D_2 is dose rate at distance r_2 from the source.

EXAMPLE 8.5

The dose rate at 2 m from a particular γ source is 400 μSv/h. At what distance will it give a dose rate of 25 μSv/h?

$$D_1 r_1^2 = D_2 r_2^2$$
$$400 \times 2^2 = 25 \times r_2^2$$
$$\therefore r_2^2 = 64$$
$$\text{and } r_2 = 8 \text{ m}$$

It will be noted that doubling the distance from the source reduces the dose rate to one-quarter of its original value, trebling the distance reduces the dose rate to one-ninth, and so on.

A useful expression for calculating the approximate dose rate from a γ point source is

$$D = \frac{ME}{6r^2}$$

where D is the dose rate in μSv/h, M is the activity of the source in MBq, E is the γ energy per disintegration in MeV and r is the distance from the source in metres.

When applying this expression, care is needed in selecting the correct units. It must be emphasized that in any real situation, protection should be based on measurements of the dose rate.

EXAMPLE 8.6

Calculate the approximate dose rate at a distance of 2 m from a 240 MBq cobalt-60 (Co-60) source. Co-60 emits two γ rays per disintegration of 1.17 and 1.33 MeV.

$$D = \frac{ME}{6r^2} \mu\text{Sv/h}$$
$$= \frac{240 \times (1.17 + 1.33)}{6 \times 2^2}$$
$$= \frac{240 \times 2.5}{24}$$
$$= 25 \, \mu\text{Sv/h}$$

EXAMPLE 8.7

Calculate the activity of a sodium-22 (Na-22) source which gives a dose rate of 64 μSv/h at 1 m. Assume that Na-22 only emits one γ photon of energy 1.28 MeV per disintegration.

Using the preceding formula:

$$64 = (M \times 1.28)/6 \times (1)^2$$
$$M = (64 \times 6)/1.28 = 300 \text{ MBq}$$

8.3.2 A LINE SOURCE

Another common geometry that is often encountered in practice is a line source such as a thin rod or a wire. In this case, the dose rate around the source does not follow a simple inverse square law.

Figure 8.1 shows a γ-emitting line source (e.g. an iridium-192 wire) between points S and T. This source is L metres long and has a total activity of M MBq. For simplicity, it can be assumed that the activity is uniformly distributed along the length, so that at any point along the line the activity per unit length is M/L MBq per metre.

To obtain an expression for the dose rate at some other point P, at a perpendicular distance of r from the line, it is useful to consider the line source to be made up of lots of tiny line sources (or sections), each Δx in length, joined end to end between S and T. Each tiny section has a tiny activity ΔM MBq such that

$$\Delta M = (M/L)\Delta x$$

Figure 8.1 shows one section about halfway along the line source. Each individual section is so tiny (i.e. so short) that it can be considered to be a point source and so, from Section 8.3.1, the dose rate at point P from this one tiny component is ΔD, where

$$\Delta D = (ME/6L) \times (\Delta x/d^2)$$

The total dose rate at point P is made up of tiny contributions from each tiny section. By summing (or integrating) all the dose rate contributions, from all the tiny sections from S to T, it can be shown that the total dose rate at P is

$$D = (ME/6Lr) \times (\theta_S - \theta_T)$$

where θ_S and θ_T are the angles (in radians) between point P and the two ends of the line source.

Note that at distances that are short in comparison to the length L of the source, the dose rate from the line source at point P reduces approximately as $1/r$ (and not $1/r^2$ as it was from a single point source). This indicates the 'cylindrical geometry' of a line source (as opposed to the 'spherical geometry' of a point source). The dose rate reduces with distance away from a line source; however, it does not drop off as quickly with distance as it does from a point source. Thus, although increasing the distance from a line source is still a valid radiation protection measure, it is not as effective as it is for a point source.

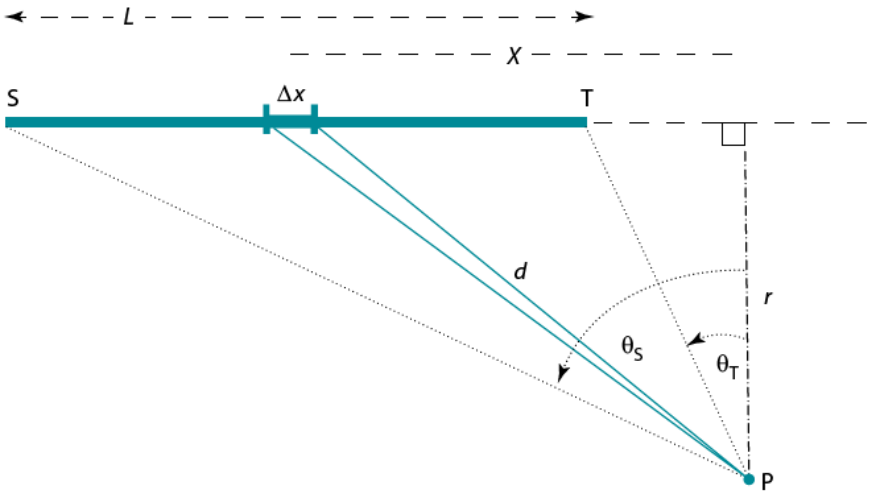


Figure 8.1 The line source.

8.3.3 A DISC SOURCE

Using a similar 'summation' method to that described for a line source in Section 8.3.2, it is possible to show that the approximate dose rate from a two-dimensional disc source is

$$D = \frac{ME}{6a^2} \ln\left[1 + \frac{a^2}{r^2}\right]$$

where D is the dose rate in μSv/h, M is the total activity of the disc source in MBq, E is the γ energy per disintegration in MeV, r is the perpendicular distance from the centre of the disc source in metres and a is the radius of the disc source in metres.

8.4 SHIELDING

The third method of controlling the external radiation hazard is by means of shielding. Generally, this is the preferred method because it results in intrinsically safe working conditions, while reliance on distance or time of exposure may involve continuous administrative control over workers.

The amount of shielding required depends on the type of radiation, the activity of the source and the dose rate which is acceptable outside the shielding material.

Alpha particles are very easily absorbed. A thin sheet of paper is usually sufficient to stop α particles and so they never present a shielding problem.

Beta radiation is more penetrating than α radiation. In the energy range that is normally encountered (up to about 4 MeV), β radiation requires shielding of up to 10 mm of Perspex for complete absorption. The ease with which β sources may be shielded sometimes leads to the erroneous impression that they are not as dangerous as γ or neutron sources and that large open β sources may be handled directly. This is an extremely dangerous practice as, for instance, the absorbed dose rate at a distance of 3 mm from a β source of 1 MBq is about 1 Gy/h.

A significant problem encountered when shielding against β radiation is the emission of secondary X-rays, which result from the rapid slowing of the β particles and which are more penetrating than the β radiation. This X radiation is known as **bremsstrahlung** and will be discussed more fully in Chapter 15, Section 15.2. The fraction of β energy reappearing as bremsstrahlung is approximately $ZE/3000$, where Z is the atomic number of the absorber and E is the maximum β energy in MeV. This means that β shields should be constructed of materials of low mass number (e.g. aluminium or Perspex) to reduce the amount of bremsstrahlung emitted.

A β source emits β particles with energies covering the complete spectrum from zero up to a characteristic maximum energy, E_{max}. The mean β energy is, in most cases, about one-third E_{max}. The penetrating power of β particles depends on their energy. This fact can be used to estimate the energy of the β radiation to aid identification of an unknown source. This will be discussed in more detail in Chapter 11, Section 11.2.

Gamma and X-ray photons interact with matter via three processes. With increasing photon energy the successively important interactions are the photoelectric effect (P-E), Compton scattering (C-S) and pair production (P-P). The cross-sections for these interactions depend on the photon energy and the atomic number of the absorbing/scattering medium. The energy ranges in which the three types of interactions become dominant are shown in Table 8.1.

γ and X radiations are attenuated exponentially when they pass through any material. The dose rate resulting from X or γ radiation emerging from a shield can be written as

$$D_t = D_0 e^{-\mu t}$$

where D_0 is the dose rate without shielding, D_t is the dose rate after passing through a shield of thickness t, and μ is the linear absorption coefficient of the material of the shield. Note that this equation is for narrow beam conditions where the source and detector are both well collimated and the measurement is

Table 8.1 Energy ranges for various photon interactions

Shielding material	Energy region of importance (MeV)		
	P-E	C-S	P-P
Low Z (e.g. water)	<0.05	0.05–15	>15
High Z (e.g. lead)	<0.5	0.5–5	>5

made at a short distance. In other situations, the presence of scattered photons often makes the calculation more complicated.

The linear absorption coefficient μ is a function of the type of material used for the shield and also of the energy of the incident photons. It has the dimensions of length^{-1} and is usually expressed in m^{-1} or mm^{-1}.

8.4.1 HALF-VALUE LAYER

The half-thickness or half-value layer (HVL) for a particular shielding material is the thickness required to reduce the intensity to one-half its incident value. Writing the HVL as $t_{1/2}$, the previous equation becomes

$$\frac{D_1}{D_0} = 0.5 = \exp(-\mu t_{1/2})$$

Taking logs to the base e:

$$\log_e 0.5 = -\mu t_{1/2}$$
$$\therefore -0.693 = -\mu t_{1/2}$$
$$\therefore t_{1/2} = \frac{0.693}{\mu}$$

The concept of HVL is very useful in doing rapid, approximate shielding calculations. One HVL reduces the intensity to one-half, two HVLs reduce the intensity to one-quarter, three HVLs to one-eighth and so on, as illustrated in Figure 8.2.

The value of μ, and hence $t_{1/2}$ depends on the material of the medium and on the radiation energy.

Another value sometimes used in shielding work is the **tenth-value layer**, $t_{1/10}$. By a calculation similar to that carried out earlier it can be shown that

$$t_{1/10} = \frac{\log_e(10)}{\mu} = \frac{2.303}{\mu}$$

Some typical values of $t_{1/2}$ and $t_{1/10}$ for lead and water are given in Table 8.2.

EXAMPLE 8.8

The dose rate close to a valve is 160 μSv/h. If this is caused by Co-60 inside the valve, how much lead shielding must be placed around the valve to reduce the dose rate to 10 μSv/h? The HVL of lead for Co-60 γ radiation is 12.5 mm.

It is required to reduce the dose rate from 160 to 10 μSv/h, that is by a factor of 16. To do this will require four HVL of lead (2 × 2 × 2 × 2 = 16), therefore 4 × 12.5 mm of lead are required, that is 50 mm.

EXAMPLE 8.9

A certain Co-60 source gives a dose rate of 40 μSv/h at 1 m. At what distance from the source must a barrier be placed if the dose rate at the barrier must not exceed 2.5 μSv/h? What thickness of lead would give the same protection at the original distance? (HVL of lead for Co-60 γ radiation is 12.5 mm.)

Assuming the Co-60 is a point source then the inverse square law applies, and so

$$40 \times (1)^2 = 2.5 \times d^2$$
$$d^2 = 40/2.5 = 16$$
$$d = \sqrt{16} = 4 \text{ metres}$$

The reduction in dose rate from 40 to 2.5 μSv/h is a factor of 40/2.5 = 16. To do this with lead shielding (instead of distance) will require four HVL of lead (2 × 2 × 2 × 2 = 16), therefore 4 × 12.5 mm of lead are required, that is 50 mm.

Particularly for gamma shielding, it is worth noting that secondary photons that have been scattered from within the shielding material itself may add to the attenuated primary beam and thus lead

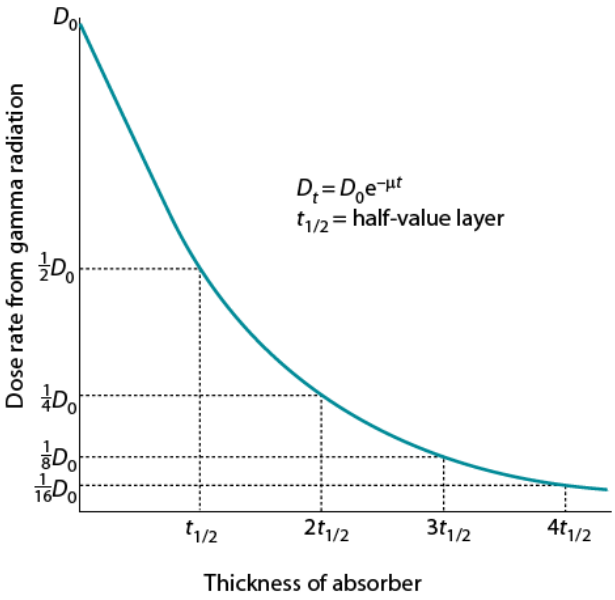


Figure 8.2 Variation of γ dose rate with absorber thickness.

Table 8.2 Approximate values of $t_{1/2}$ and $t_{1/10}$

γ Radiation (energy [MeV])	Millimetres of lead		Millimetres of water	
	$t_{1/2}$	$t_{1/10}$	$t_{1/2}$	$t_{1/10}$
0.5	4	12.5	150	500
1.0	11	35	190	625
1.5	15	50	210	700
2.0	19	60	225	750

to higher than expected dose rates at points outside the barrier. This is quantified by using a **build-up factor**, which is the ratio of the total dose (including the dose from secondary photons) at a point outside the shielding to the primary photon dose at the same point. The primary dose comes from original photons that have penetrated the shielding material without interacting. Magnitudes of build-up factors vary widely, ranging from a minimum of 1.0 to very large values, depending on source and shield characteristics.

And so the aforementioned narrow beam formula for exponentially attenuated photons is modified to

$$D_t = D_0 b e^{-\mu t}$$

where b is the build-up factor.

Build-up factors depend on photon energy, the shielding material and its thickness. This means that iterative calculations must be carried out in order to obtain an approximate value for the thickness of shielding required to give a specified dose rate at a particular dose point outside the shield. Useful references for carrying out such calculations are 'BS 4094: Data on Shielding from Ionising Radiation – Part 1: Shielding from Gamma Radiation' and 'Part 2: Shielding from X-Radiation'.

Neutron shielding is complicated by the very wide range of neutron energies generally encountered. This means that any shielding equipment has to take account of a number of different energy-related reactions, the most important of which are:

1. **Elastic scatter**, in which the neutron collides with the target nucleus and 'bounces' off it in a manner similar to the collision of two billiard balls. During the collision, the neutron loses some of its initial energy and this energy is transferred to the target nucleus. All of this transferred energy appears as kinetic energy of the target nucleus. Light elements are best for slowing down neutrons by elastic scatter and so materials with a high hydrogen content (such as paraffin, water, concrete) are used.
2. **Inelastic scatter**, in which the incoming neutrons impart some of their energy to the scattering material and excite the target nuclei. These target nuclei usually emit γ radiation later when they return to their ground state. The inelastic scatter process is most important for heavy nuclei.
3. **Neutron capture** reactions are of many kinds. In these reactions neutrons are captured by nuclei which then de-excite by emitting another particle or photon. One very important neutron capture reaction is

$$^{10}\mathrm{B}(\mathrm{n},\alpha)^{7}\mathrm{Li}$$

The importance of this reaction, from a shielding point of view, lies in the fact that the emitted α particle is very easily absorbed. Thus, the incorporation of boron-10 (B-10) in shields means that thermal neutrons are absorbed and the resulting α particles cause no further shielding problems.

Unfortunately, the most common neutron capture reactions lead to the emission of penetrating γ radiation, for example as in cadmium-113 (Cd-113):

$$^{113}\mathrm{Cd}(\mathrm{n},\gamma)^{114}\mathrm{Cd}$$

Capture γ radiation is usually a limitation in shield design and a material of high atomic number is often incorporated to absorb capture γ radiation. Nevertheless, owing to its relatively high efficiency for capturing thermal neutrons (high thermal neutron 'cross-section'), cadmium is commonly used in neutron shields.

Shielding for fast (or intermediate) neutrons might exploit elastic scatter and neutron capture by incorporating B-10 into a material with a high hydrogen content, for example boronated polythene.

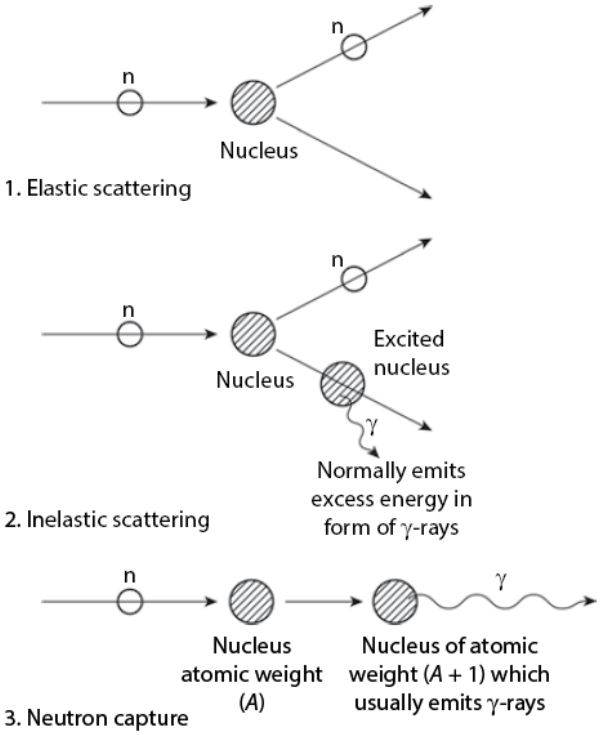


Figure 8.3 The three main neutron reactions.

The fast neutrons are first 'thermalized' by elastic scatter in the polythene and then captured by the boron.

The neutron reactions are illustrated schematically in Figure 8.3.

8.5 NEUTRON SOURCES

Nuclear fission reactors are the source of large fluxes of neutrons (see Chapter 13, Section 13.2). However, there are simpler methods for producing relatively small neutron sources. The most commonly used depends on the reaction

$$^{9}\mathrm{Be}(\alpha, \mathrm{n})^{12}\mathrm{C}$$

A typical neutron source of this type consists of a quantity of the element beryllium (Be) mixed with an α-emitting radionuclide, usually americium-241 (Am-241), in a sealed capsule. For Am/Be sources, the source strength is about 70 neutrons per second per MBq of Am-241. The spectrum of neutrons emitted from an α-beryllium source is not mono-energetic but is highly peaked at energies between 3 and 6 MeV; in other words, these neutron sources produce mainly fast neutrons.

Another reaction used to produce neutrons is the photoneutron process, which utilizes the (γ, n) reaction. The most common type of photoneutron source consists of a mixture of equal volumes of antimony and beryllium, in which high-energy γ rays from antimony-124 (Sb-124) interact with beryllium nuclei causing the ejection of neutrons. It is worth noting that the neutrons produced by the (γ, n) process are, for most practical purposes, mono-energetic.

Yet another source of neutrons can be from radioisotopes that undergo spontaneous fission, such as californium-252 (Cf-252), where each fission event typically results in the emission of two to four neutrons with an energy spectrum similar to that from a nuclear fission reactor and an average neutron energy of approximately 2 MeV.

To calculate the flux at a distance r from a source of strength Q, the following expression is used (see Chapter 3):

$$\Phi = \frac{Q}{4\pi r^2}$$

EXAMPLE 8.10

Calculate the neutron dose rate at 1 m from a 0.1 TBq Am/Be source (1 TBq of ^{241}Am/Be emits 7×10^7 n/s). Assume that 10^4 n/m^2/s is equivalent to 1 μSv/h.

The surface area (A) of a sphere with a radius of 1 m is:
$A = 4\pi r^2 = 4 \times \pi \times (1)^2 = 12.6$ m^2

0.1 TBq Am/Be emits: $0.1 \times 7 \times 10^7 = 7 \times 10^6$ n/s

Flux of neutrons over the surface area of the sphere = $7 \times 10^6/12.6 = 5.6 \times 10^5$ n/m^2/s
So the dose rate = $5.6 \times 10^5/10^4 = 56$ μSv/h

8.6 PERSONAL DOSE CONTROL

In the United Kingdom, routine control of personal dose is based on a system of area classification. Various systems and terminologies are in use. The basic objective is to segregate areas according to the radiological hazard. In areas where the exposure is unlikely to exceed one-tenth of the occupational

8.7 Principles of Radiation Protection

Of the various types of radiation, the α-particle is most damaging because of its charge and great mass, followed in order by the b-particle and the g- ray. Heavier particles have shorter ranges and therefore deposit more energy per unit path length in the absorber, causing more damage. On the other hand, γ-rays and x-rays have no charge or mass and therefore have a longer range in matter and cause relatively less damage in tissue. Knowl- edge of the type and energy of radiations is essential in understanding the principles of radiation protection.

The cardinal principles of radiation protection from external sources are based on four factors: time, distance, shielding, and activity.

Time

The total radiation exposure to an individual is directly proportional to the time of exposure to the radiation source. The longer the exposure, the higher the radiation dose. Therefore, it is wise to spend no more time than necessary near radiation sources.

Distance

The intensity of a radiation source, and hence *the radiation exposure, varies inversely as the square of the distance from the source to the point of expo- sure*. It is recommended that an individual should keep as far away as prac- tically possible from the radiation source. Procedures and radiation areas should be designed so that individuals conducting the procedures or staying in or near the radiation areas receive only minimum exposure.

The radiation exposure from γ-ray and x-ray emitting radionuclides can be estimated from the *exposure rate constant*, Γ, which is defined as the exposure from g-rays and x-rays in R/hr from 1 mCi (37 MBq) of a radionuclide at a distance of 1 cm. Each g- and x-ray emitter has a specific value of Γ, which has the unit of $R \cdot cm^2/mCi \cdot hr$ at 1 cm or, in System Internationale (SI) units, $mGy \cdot$

m^2/GBq · hr at 1 m. The G values are derived from the number of γ-ray and x-ray emissions from the radionuclide, their energies, and their mass absorption coefficients in air. Because γ-rays or x-rays below some 10 or 20 keV are absorbed by the container and thus do not contribute significantly to radiation exposure, often g-rays and x-rays above these ener- gies only are included in the calculation of G.

Shielding

Various high atomic number (Z) materials that absorb radiations can be used to provide radiation protection. Because the ranges of □- and □- particles are short in matter, the containers themselves act as shields for these radiations. γ-Radiations, however, are highly penetrating. Therefore, highly absorbing material should be used for shielding of γ-emitting sources, although for economic reasons, lead is most commonly used for this purpose. The half-value layer (HVL) of absorbent material for different radiations is an important parameter in radiation protection and is related to linear attenuation coefficient of the photons in the absorbing material.

Obviously, shielding is an important means of protection from radiation. Radionuclides should be stored in a shielded area. The radiopharmaceuti- cal dosages for patients should be carried in shielded syringes. Radionu- clides emitting β-particles should be stored in containers of low-*Z* material such as aluminum and plastic because in high-*Z* material, such as lead, they produce highly penetrating bremsstrahlung radiations. For example, ^{32}P is a β^- emitter and should be stored in plastic containers instead of lead containers.

SUMMARY OF KEY POINTS

- **External radiation hazard** arises from radioactive materials outside the body.
- **Control of external hazard:** Time, distance and shielding.
- **Time:** Dose = Dose rate × Time.
- **Distance:** Inverse square law $D_1 r_1^2 = D_2 r_2^2$.

  Dose rate from a γ source is

$$D = \frac{ME}{6r^2}\ \mu\text{Sv/h}$$

  (M in MBq, E in MeV, r in metres).
- **Shielding:** *Alpha* particles very easily absorbed.

  Beta radiation. Use low Z materials to reduce bremsstrahlung.

  Gamma radiation is attenuated exponentially:

$$D_t = D_0 e^{-\mu t}$$
$$\text{HVL} = t_{1/2} = 0.693/\mu$$

- **Neutron shielding:** Elastic scatter, inelastic scatter and neutron capture.
- **Neutron sources** depend on either (α, n) or (γ, n) reactions.
- **Area classification:** Non-designated, supervised, controlled and restricted areas.

- **X and γ monitors** use ion chambers, Geiger–Müller tubes or scintillation detectors.
- **Neutron monitors** ideally cover the energy range from thermal up to about 15 MeV and use the reaction $^3\text{He(n, p)}^3\text{H}$ to give good γ rejection.
- **Personal dosimeters:**
  - **Thermoluminescent dosimeters** (TLDs) store the radiation energy which can later be released by heating. The light output is measured using a photomultiplier tube, the electrical output of which is a measure of the radiation dose.
  - **Optically stimulated luminescent dosimeters** are similar to TLDs but are read with the intense light from either a laser or a light-emitting diode.
  - **Personal electronic dosimeters** are based on solid-state detectors and provide both short-term and long-term measurement capability with direct readout.
  - **Fast neutron track plate** is a special film in a holder; fast neutrons eject recoil protons which cause developable tracks in the emulsion. Main disadvantage is that track detectors are expensive to evaluate.
  - **Criticality locket** is worn when handling fissile material; the various components are activated by neutrons of different energy and can be counted in a β castle.

CHAPTER 7
The internal radiation hazard

9.1 UNCONTAINED RADIOACTIVITY

When a radioactive material is enclosed inside some form of sealed container, it may give rise to an external radiation hazard to personnel working in its vicinity. Conversely, when radioactive material is not contained in any way it also constitutes a potential **internal radiation hazard**. Uncontained radioactive material is generally referred to as **contamination**.

Quite small quantities of radioactive material, which represent an insignificant external hazard, can give rise to appreciable dose rates if they come into contact with, or get inside, the body. Once the radioactive substance is taken into the body, it will continue to irradiate the body until either the radioactivity has decayed or the body has excreted the substance. The rate of decay of the radioactivity depends on its half-life, which can vary from a small fraction of a second to many thousands of years. The rate of excretion of the substance from the body depends mainly on its chemical characteristics, and it may happen in a period of a few days or it may take much longer, perhaps many years. Thus, when a radioactive substance enters the body, it may irradiate it for only a few days or for a much longer period that may extend to many years in the case of some nuclides.

9.2 ROUTES OF ENTRY

There are three ways in which radioactive material can enter the body. These are

- **inhalation** of airborne contamination;
- **ingestion**, that is entry through the mouth; and
- **entry via the skin by** absorption, through a contaminated wound or by injection, such as during a nuclear medicine procedure (see Chapter 16, Section 16.5).

It should be noted that contamination can also result in direct irradiation of the skin.

When airborne contamination is inhaled, a proportion of the radioactivity is deposited in the lungs and the respiratory tract and the remainder is exhaled. Some of the deposited material is eliminated from the lungs quite quickly and is swallowed. The material remaining in the lungs may then be absorbed at a greater or lesser rate into the bloodstream, be transported to other body organs and eventually be excreted. The fraction initially deposited and its rate of clearance depends on many factors, such as the physical and chemical form of the material and the metabolism of the person involved. Generally, materials in an insoluble form can remain in the lungs and continue to irradiate them for many years (depending on the half-life) while more soluble forms of material will be cleared from the lungs into other body organs, which will in turn be subject to irradiation until the material decays or is excreted. Similarly, when contamination is ingested, the amount of it passing through the wall of the digestive tract into the body fluids and into body organs depends on the nature of the contamination and on metabolic and physiological factors.

There are wide variations in the characteristics of human beings and, in order to provide a consistent basis for radiation dose calculations,

the International Commission on Radiological Protection (ICRP) has defined a set of reference values of anatomical and physiological data, reported in Publication 89. This provides a series of reference values for both male and female subjects of six different ages: newborn, 1, 5, 10, 15 years and adult. Some examples of the reference data for an adult male are shown in Table 9.1.

It was pointed out earlier that the fate of a particular radionuclide inside the body depends on its chemical and physical form. For example, some elements distribute themselves fairly uniformly and so irradiate the whole body at about the same rate. The majority of elements, however, tend to concentrate in particular organs so that an intake of radioactivity may result in different dose rates to the various organs of the body. Examples of such elements are iodine, which concentrates in the thyroid gland, and plutonium, which concentrates in the lung or bone.

The dose rate to any organ is proportional to the amount of radioactivity in the organ and decreases as the radioactivity decays or is excreted. The decay of a radionuclide is exponential in character and it is found that the rate of excretion of most substances from the body may also be considered as approximately exponential. This means that an **effective decay constant** can be employed to describe the rate of removal of a radioactive substance from the body (see Figure 9.1), namely

$$\lambda_{\text{eff}} = \lambda_{\text{r}} + \lambda_{\text{b}}$$

where λ_{r} is the radioactive decay constant and λ_{b} is the biological decay constant.

Since the decay constant is inversely proportional to the half-life, this equation becomes

$$\frac{1}{T_{\text{eff}}} = \frac{1}{T_{\text{r}}} + \frac{1}{T_{\text{b}}}$$

where T_{eff} is the effective half-life of a radioactive substance in the body, T_{r} is the radioactive half-life of the substance and T_{b} is the biological half-life of the substance.

Figure 9.2 illustrates the variation of dose rate with time following an intake of a radionuclide. The initial rise in the curve covers the period during which the nuclide is being transported to the organ of interest. At the peak, most of the radionuclide that is destined for the particular organ has reached it and the organ is receiving its maximum dose rate. Subsequently, the dose rate to the organ decreases approximately exponentially as the radionuclide decays and is excreted. The total dose received by the organ is obtained by evaluating the area under the curve. Thus, a given intake of a radionuclide will 'commit' the organ (or organs) at risk from that nuclide to a certain dose, which is known as the **committed equivalent dose**. This depends on the initial dose rate and on the removal rate. It is usually assumed that a given intake of a particular radionuclide will result in the same committed equivalent dose whether it is received in a single large intake or a large number of small intakes.

For the majority of radionuclides, the dose is received over a relatively short period following an

Table 9.1 Some characteristics of reference man

Organs of reference man

Organ	Mass (kg)	Percentage of total body
Total body	73	100
Skeleton	10.5	14
Muscle	29	40
Fat	14.6	20
Blood	5.6	7.7
Gastrointestinal tract (including contents)	2.3	3.2
Thyroid gland	0.02	0.027

Water balance

Water intake (L/day)		Excretion (L/day)	
Foods and fluids	2.6	Urine	1.6
Oxidation	0.3	Sweat	0.5
		Insensible	0.69
		Faeces	0.11
Total	2.9	Total	2.9

Air balance

Air inhaled during 8 h working day	9.6 m³
Air inhaled during 16 h not at work	13.3 m³
Total	~23 m³/day

Note: These values are for the adult male. In most cases, the values for adult female are lower. For full details of the characteristics of reference man, see ICRP Publication 89.

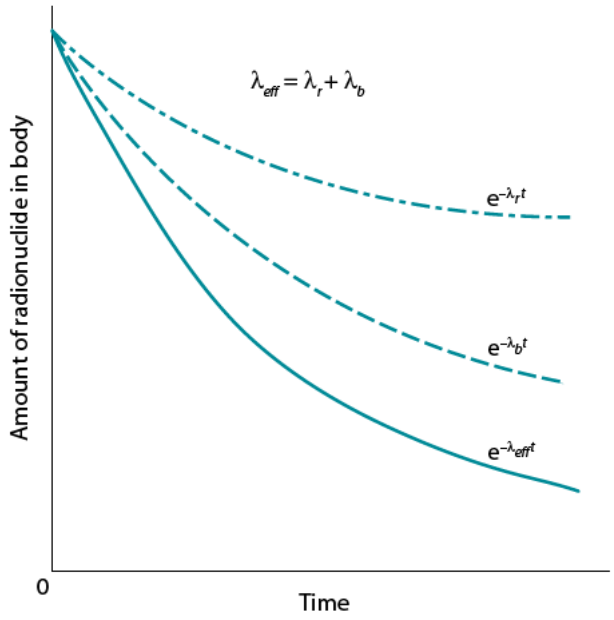


Figure 9.1 Typical elimination curve of a radionuclide in the body.

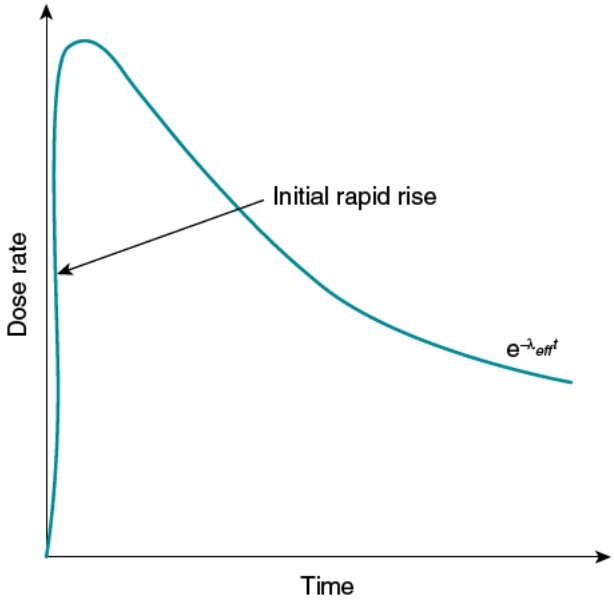


Figure 9.2 Variation of dose rate with time following an intake of a radionuclide.

intake, typically a few months to a few years, because after this time the radioactivity will have decayed or have been excreted. For some long-lived species, such as plutonium isotopes, the radioactivity is excreted very slowly and so the dose is received over a very long period. In this latter case, the committed dose is defined as the dose that is received in a period following the intake of 50 years for adults or up to age 70 years for children, as these times represent the likely maximum lifespan of the individual following the intake. The committed effective dose is the committed equivalent dose multiplied by the tissue weighting factor(s) (see Chapter 3, Section 3.5).

9.3 ASSESSMENT OF DOSE

9.3.1 DOSE COEFFICIENT

The ICRP has calculated values of the committed effective dose for an intake of 1 Bq for virtually all radionuclides that could be of interest in radiation protection. These are referred to as **committed effective dose coefficients for intakes,** usually shortened to **dose coefficients**. Separate values are given for intake by inhalation and ingestion. The basic values for workers and members of the public, including infants and children, are tabulated in Publication 119, which is freely available online at *http://www.icrp.org/publication.asp?id=ICRP%20Publication%20119*. It should be noted that the dose coefficients given in Publication 119 are based on data such as tissue weighting factors given in Publication 60, which has since been superseded by Publication 103. Revised dose coefficients will be published by the ICRP in due course.

Table 9.2 illustrates some examples of the dose coefficients for some important radionuclides for inhalation and ingestion. Since the transfer of any material from the lung or from the gut is influenced by its chemical form, particularly its solubility, it is necessary to specify different values for different chemical forms of the majority of radionuclides. It can be seen that the committed effective dose from an intake of 1 Bq varies widely for different radionuclides reflecting the different types of emission (α or β), the half-life and the behaviour of the particular chemical form of a radionuclide in the body. Radionuclides with a high dose coefficient are of high radiotoxicity and those with a low value are of low radiotoxicity.

It should be noted that the values recommended by the ICRP are revised periodically in the light of new scientific data and so values from current sources should always be used for radiation protection purposes.

Table 9.2 Some values of dose coefficients for workers

Radionuclide	Compound	Dose coefficient (Sv/Bq)	
		Inhalation	Ingestion
Tritium (H-3)	Tritiated water	1.8×10^{-11}	1.8×10^{-11}
	Organically bound	4.1×10^{-11}	4.2×10^{-11}
	Hydrogen gas	1.8×10^{-15}	–
Sodium-22 (Na-22)	All	2.0×10^{-9}	3.2×10^{-9}
Iodine-131 (I-131)	All	1.1×10^{-8}	2.2×10^{-8}
Caesium-137 (Cs-137)	All	6.7×10^{-9}	1.3×10^{-8}
Plutonium-239 (Pu-239)	Insoluble oxides	8.3×10^{-6}	9.0×10^{-9}
	Nitrates	–	5.3×10^{-8}
	All other compounds	3.2×10^{-5}	2.5×10^{-7}

Source: International Commission on Radiological Protection. 2012. Compendium of dose coefficients based on ICRP Publication 60. ICRP Publication 119. *Ann ICRP* 41 (Suppl.).
Note: Inhalation dose coefficients are for the default particle size of 5 μm.

EXAMPLE 9.1

During a particular year, it is estimated that a worker has been exposed to intakes of 1.5×10^5 Bq of Na-22 (via ingestion) and 50 Bq of Pu-239 oxide (via inhalation). What is the total committed effective dose from the intakes?

For Na-22, the ingestion dose coefficient is 3.2×10^{-9} Sv/Bq and for Pu-239 in oxide form the inhalation dose coefficient (5 μm) is 8.3×10^{-6} Sv/Bq (see Table 9.2). The committed effective dose from the intakes is then

For Na-22: 1.5×10^5 Bq $\times$ 3.2×10^{-9} Sv/Bq
$= 4.8 \times 10^{-4}$ Sv $= 0.48$ mSv

For Pu-239: 5.0×10^1 Bq $\times$ 8.3×10^{-6} Sv/Bq
$= 0.42$ mSv

The total dose is therefore 0.90 mSv.

It should again be emphasized that in radiation protection the primary requirement is not just to maintain doses within the dose limits but to ensure that doses are as low as reasonably achievable within those dose limits. This is particularly important in the case of internal radiation because of the greater difficulty in controlling exposure and of assessing the doses to individuals from intakes of radioactivity.

In assessing the total dose received by a person in a year, both the external and internal doses must be considered to ensure that the recommended dose limit is not exceeded. For this purpose, the committed dose should be assigned to the year in which the intake occurred, even though some, or perhaps most, of the dose will not be received for many years.

9.3.2 ANNUAL LIMIT OF INTAKE

The annual limit of intake for any radionuclide is the intake of the radionuclide which would result in an individual receiving a dose equal to the dose limit and is obtained by dividing the annual dose limit (0.02 Sv) by the appropriate dose coefficient.

9.4 CONTROL OF THE CONTAMINATION HAZARD

9.4.1 BASIC PRINCIPLES

As with external radiation, the consideration in the control of the radioactive contamination hazard is to ensure that doses are as low as reasonably achievable and that the relevant dose limits are not exceeded. However, the basic approaches to controlling exposure are quite different. In the case of external radiation, the dose rate in a working area can be easily measured, and the dose received by workers can be continuously monitored and controlled using personal dosimeters. Where there is significant radioactive contamination, however, there is much greater uncertainty both in the levels of radioactivity on surfaces and in the air in the workplace and, particularly, in the quantities likely to be inhaled or ingested

SUMMARY OF KEY POINTS

- **External radiation hazard** arises from radioactive materials outside the body.
- **Control of external hazard:** Time, distance and shielding.
- **Time:** Dose = Dose rate × Time.
- **Distance:** Inverse square law $D_1 r_1^2 = D_2 r_2^2$.
  Dose rate from a γ source is

$$D = \frac{ME}{6r^2}\ \mu\text{Sv/h}$$

  (M in MBq, E in MeV, r in metres).
- **Shielding:** *Alpha* particles very easily absorbed.
  Beta radiation. Use low Z materials to reduce bremsstrahlung.
  Gamma radiation is attenuated exponentially:

$$D_t = D_0 e^{-\mu t}$$
$$\text{HVL} = t_{1/2} = 0.693/\mu$$

- **Neutron shielding:** Elastic scatter, inelastic scatter and neutron capture.
- **Neutron sources** depend on either (α, n) or (γ, n) reactions.
- **Area classification:** Non-designated, supervised, controlled and restricted areas.

SUMMARY OF KEY POINTS

- **Internal radiation hazard:** Caused by radioactive materials inside the body.
- **Routes of entry:** Inhalation, ingestion and direct entry by absorption or through wounds in the skin.
- **Effective decay constant:** $\lambda_{\text{eff}} = \lambda_r + \lambda_b$.
- **Committed equivalent dose to an organ:** The equivalent dose to which an organ is committed following an intake.
- **Committed effective dose:** The committed equivalent dose to an organ multiplied by the appropriate tissue weighting factor(s).
- **Dose coefficient:** The effective dose from an intake of 1 Bq of a radionuclide. ICRP has tabulated values for all radionuclides of interest for both inhalation and ingestion.
- **Surface contamination monitoring:** Direct monitoring using scintillation detectors or Geiger–Müller tubes; indirect monitoring using smear surveys.
- **Airborne contamination monitoring:**
  - **Particulate** contamination level determined by drawing a known volume of air through a filter paper.
  - **Gaseous** activity measured by drawing a known volume of the atmosphere through a charcoal filter into a sample chamber and counting the activity.
- **Personal monitoring:**
  - *γ emitters*: Whole-body counter/monitor
  - *α or β emitters*: Faeces or urine monitoring
  - Personal air sampling

Sources of Radiation Exposure

The population at large receives radiation exposure from various sources such as natural radioactivity, medical procedures, consumer products, and occupational sources. The estimates of annual effective dose equivalents from different radiation sources to the U.S. population are tabulated in Table 16.1.The major contribution of the exposure comes from natural sources, particularly from radon from building materials, amounting to 200 mrem (2 mSv)/year accounting for 82% of the total exposure. Excluding radon exposure, the average exposure from natural background consisting of cos- mic radiations, terrestrial radiations, and so on amounts to about 100 mrem (1 mSv)/year. This exposure varies with the altitude of places above sea level. For example, the annual cosmic ray exposure in cities such as Denver is about 50 mrem (0.5 mSv) compared to 26 mrem (0.26 mSv) at sea level. Air travel at a height of 39,000 ft (12 km) gives 0.5 mrem/hr (5 mSv/hr), resulting in an annual dose of 1 mrem (10 mSv) to the population.

Terrestrial radiation exposure arises from radionuclides such as ^{40}K and from decay products of thorium and uranium in soil. It varies from about 16 mrem (160 mSv)/year in the Atlantic ocean to 63 mrem (630 mSv)/year in the Rockies with an average of 28 mrem (280 mSv)/year.

Radionuclides ingested through food, water, or inhalation include ^{40}K and decay products of thorium and uranium, particularly ^{210}Po, and contribute about 39 mrem (390 mSv) annually.

Man-made exposure constitutes about 18% of the total exposure. Medical procedures contribute the highest exposure of all man-made radiation sources. The most exposure comes from diagnostic radiographic procedures with about 39 mrem (390 mSv) annually compared to 14 mrem (140 mSv) for nuclear medicine procedures. Exposure from radiation therapy is relatively small.

Consumer products such as tobacco, water supply, building materials,

agricultural products, and television receivers contribute to radiation expo-

Table Annual effective dose equivalent in the U.S. population from different sources circa 1980 to 1982

Sources	Average annual effective dose equivalent in mrem (mSv)
Natural sources	
Radon	200 (2.0)
Cosmic rays	27 (0.27)
Terrestrial	28 (0.28)
Ingested radionuclides	39 (0.39)
Medical procedures	
Diagnostic x-rays	39 (0.39)
Nuclear medicine	14 (0.14)
Radiation therapy	<1 (0.01)
Consumer products	5–13 (0.05–0.13)
Occupational	0.9 (0.009)
Nuclear fuel cycle	0.05 (0.0005)
Miscellaneous	0.06 (0.0006)
Total	~360 (3.6)

Adapted with permission from NCRP Report No. 93. *Ionizing Radiation Exposure of the Population of the United States*. Bethesda, MD: NCRP; 1987:

Tables 6.1 and 2.4. sure through consumption. Exposure from smoking has been estimated to be 1.3 mrem (13 mSv)/year, which is not included in Table 7.1, because it is difficult to calculate the collective effective dose equivalent for the entire population. The total exposure from consumer products varies between 5 and 13 mrem (50 and 130 mSv)/year.

Occupational exposure is received by the workers in reactor plants, coal mines, and other industries using radionuclides. This value is about 0.9 mrem (9 mSv)/year, which is quite small, because a great deal of precaution is taken to reduce exposure in the workplace.

Nuclear power plants around the country release small amounts of radionuclides to the environment, which cause radiation exposure to the population. This value is of the order of 0.05 mrem (0.5 mSv)/year.

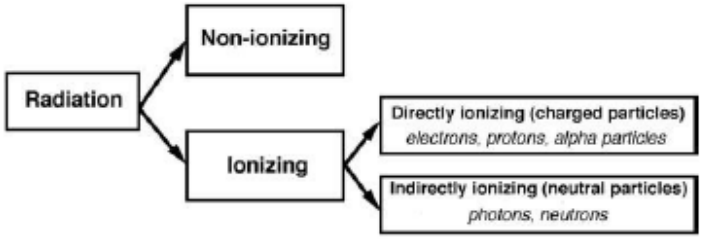
Types of Radiation

- Radiation is classified into:
  - –Ionizing radiation
  - –Non-ionizing radiation

Ionization

- **Ionizing radiation is produced by unstable atoms. Unstable atoms differ from stable atoms because they have an excess of energy or mass or both.**
- **Unstable atoms are said to be radioactive. In order to reach stability, these atoms give off, or emit, the excess energy or mass. These emissions are called radiation.**

Classification of Radiation

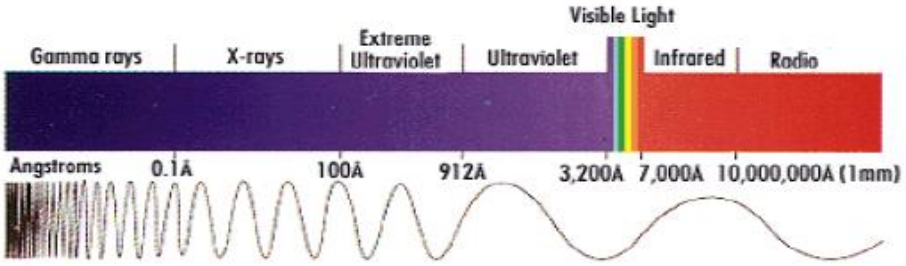


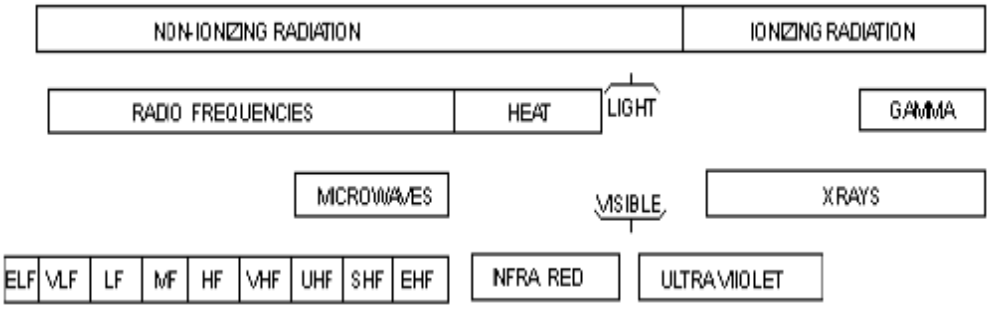
• ***Non-ionizing*** *radiation cannot ionize matter because its energy is lower* than the ionization potential of matter.
• ***Ionizing radiation*** *can ionize matter either directly or indirectly because* its energy exceeds the ionization potential of matter. It contains two major categories:
– ***Directly ionizing radiation*** *(charged particles) electrons, protons, alpha particles, heavy ions*
– ***Indirectly ionizing radiation*** *(neutral particles) photons (x rays, gamma rays), neutrons*

Ionizing Versus Non-ionizing Radiation

- **Ionizing Radiation**
  - **– Higher energy electromagnetic waves (gamma) or heavy particles (beta and alpha).**
  - **– High enough energy to pull electron from orbit.**
- **Non-ionizing Radiation**
  - **– Lower energy electromagnetic waves.**
  - **– Not enough energy to pull electron from orbit, but can excite the electron.**

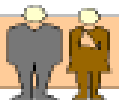
- The electro-magnetic waves vary in their length and frequency along a very wide spectrum.





Primary Types of Ionizing Radiation	X-Rays
■ Alpha particles ■ Beta particles ■ Gamma rays (or photons) ■ X-Rays (or photons) ■ Neutrons	X-Rays: Occur whenever an inner shell orbital electron is removed and rearrangement of the atomic electrons results with the release of the elements characteristic X-Ray energy
• ***X-*** *and* ***Gamma Rays***: **X-rays** are photons (Electromagnetic radiations) emitted **from electron orbits**. **Gamma rays** are photons emitted **from the nucleus**, often as part of radioactive decay. Gamma rays typically have higher energy (Mev's) than X-rays (KeV's), but both are unlimited.	Neutrons: Have the same mass as protons but are uncharged

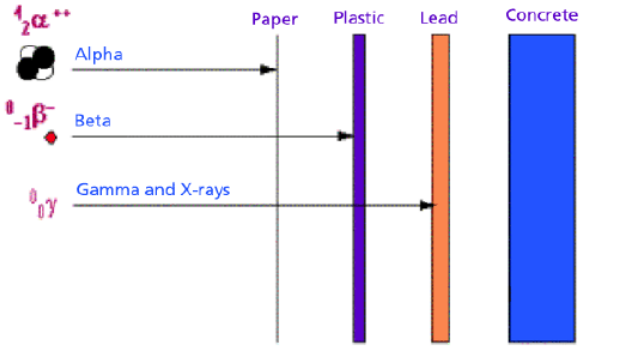
Radiation from Natural Sources

	Source	mrem/year
	Cosmic rays	28
	The earth	26
	Radon	200
	The human body	25
	Building materials	4

Radiation from Manmade Sources

Source	mrem/year
Medical	90
Fallout	5
Consumer products	1
Nuclear power	0.3

Penetrating Distances



Non-ionizing Radiation

- Definition:

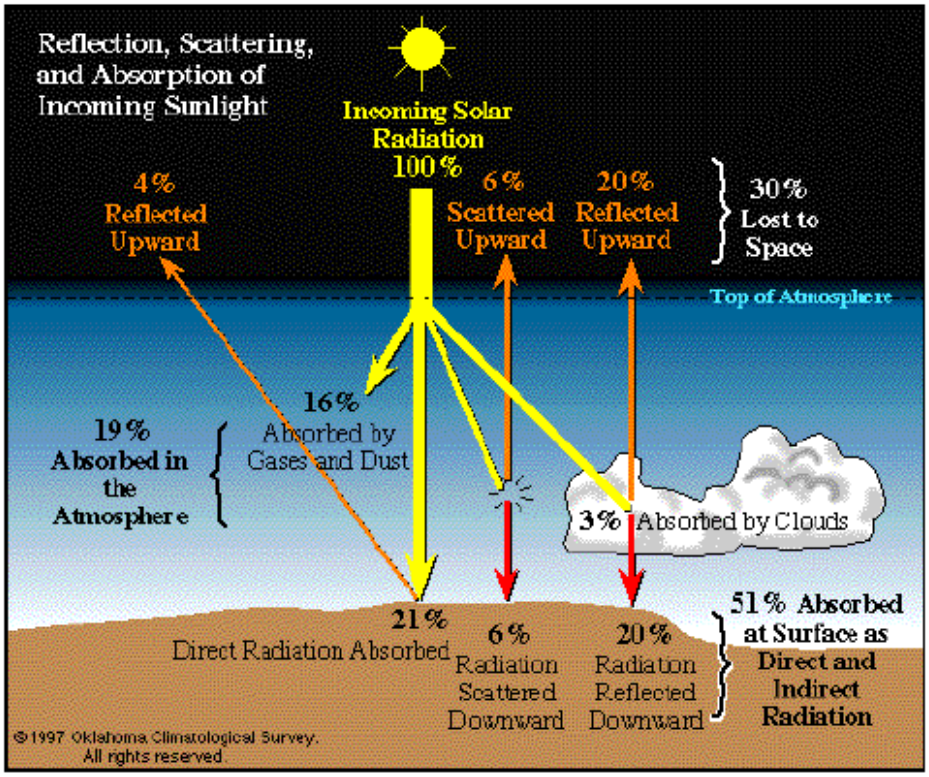
" They are electromagnetic waves incapable of producing ions while passing through matter, due to their lower energy."

- The sun emits radiation composed of high energy infrared radiation, visible light, and ultraviolet radiation collectively known as shortwave radiation (SW)
- The earth emits radiation composed of lower energy infrared radiation collectively known as long-wave radiation (LW)

Effects

- Radiofrequency Ranges (10 kHz to 300 GHz)
  - Effects only possible at ten times the permissible exposure limit
  - Heating of the body (thermal effect)
  - Cataracts
  - Some studies show effects of teratoginicity and carcinogenicity.

- A. Basic Control Methods for External Radiation
  - Decrease Time
  - Increase Distance
  - Increase Shielding



امثلة محلولة

أ) تركيب النواه

- تتركز النواة في جسم صغير ذي شحنة موجبة تسمى نواة الذرة Nucleus
- تحتوي النواة على بروتونات (P)و نيوترونات (N) وتسمى البروتونات أو النيوترونات بالنيوكلونات
- يرمز لأي عناصر بـ $^{A}_{Z}X$
- حيث Z هو العدد الذري ويساوي عدد البروتونات (P) بالنواة وكذلك يساوي عدد الإلكترونات (e) بالذرة المتعادلة كهربيا
- و A هو العدد الكتلي ويساوي مجموع عدد النيوترونات والبروتونات (A=N+Z)

ج) كتلة النواة:

تقاس كتلة النواة بوحدة الكتلة الذرية (و.ك.ذ.) (u):

١/١٢ من كتلة ذرة نظير الكربون-١٢ ، أي ان كتلة ذرة الكربون-١٢ تساوي ١٢ ك.و.ذ.

$$1\ u = 1.660566 \times 10^{-27}\ kg = 931.5\ MeV/c^2$$

حساب الطاقة المكافئة لكتلة ذرية واحدة:

$$m=1u$$
$$E= mc^2 = 1u \times c^2$$
$$= 1.660566 \times 10^{-27}\ kg \times (3\times10^{8}\ m/s)^2$$
$$= 0.149 \times 10^{-9}\ j$$
$$= 0.149 \times 10^{-9}\ j / 1.6\times10^{-19}\ j/MeV$$
$$= 931.5\ MeV$$

حساب الطاقة المكافئة لكتلة ذرية واحدة:

$$m=1u$$
$$E= mc^2 = 1u \times c^2$$
$$= 1.660566 \times 10^{-27}\ kg \times (3\times10^{8}\ m/s)^2$$
$$= 0.149 \times 10^{-9}\ j$$
$$= 0.149 \times 10^{-9}\ j / 1.6\times10^{-19}\ j/MeV$$
$$= 931.5\ MeV$$

Particle	kg	u	MeV/
Proton	$1.672\,62 \times 10^{-27}$	1.007 276	938.28
Neutron	$1.674\,93 \times 10^{-27}$	1.008 665	939.57
Electron	$9.109\,39 \times 10^{-31}$	$5.48\,579 \times 10^{-4}$	0.510 999
$^{1}_{1}$H atom	$1.673\,53 \times 10^{-27}$	1.007 825	938.783
$^{4}_{2}$He nucleus	$6.644\,66 \times 10^{-27}$	4.001 506	3 727.38
$^{12}_{6}$C atom	$1.992\,65 \times 10^{-27}$	12.000 000	11 177.9

د – حجم النواة:

نصف قطر النواة ⟸ $r \approx 10^{-15}\,m$

نصف قطر الذرة ⟸ $r \approx 10^{-11}\,m$

يتناسب مكعب نصف قطر النواة طردياً مع A

$$A \alpha r^3 \rightarrow r \alpha A^{1/3}$$

$$r = r_0 A^{1/3} = 1.2x10^{-15} A^{1/3}$$

حجم النواة: $V = \frac{4}{3}\pi r^3 = (\frac{4}{3}\pi r_0^3) A$

الكثافة: $\rho = \frac{m}{V}$ ⟸ $\rho = \frac{m}{V} = \frac{Ax1.660566x10^{-27}\,kg}{(\frac{4}{3}\pi r_0^3) A} = 2.3x10^{17}\,kg/m^3$

لجميع النوى

3-14 استقرار النواة:

القوى النووية أكبر من قوة التنافر الكهربية بين البروتونات بحوالي 40 مرة. لا يظهر أثرها عند المسافات الكبيرة. تعمل على جذب كل النيوكلونات بالنواة ولا تعتمد على الشحنة الكهربية للجسيمات.

4-14 الطاقة الرابطة النووية Nulear Binding Energy

كتلة النواة < مجموع كتلة البروتونات + النيوترونات

$$M = Z*m_P + Z*m_e + N*m_n$$

$$B.E. = [Mcal - Mexpt.]\ x931.5MeV$$

$$B.E.(MeV) = \left[\left(Z*m_P + Z*m_e + N*m_n\right) - \left(M\ {}^{A}_{Z}X\right)\right](u)\ *931.5(MeV/u)$$

مثال 14-2 :

$$M\left({}^{56}_{26}Fe\right) = 55.934937u$$

$$B.E. = \left[n_p.m_p + n_p.m_e + n_n.m_n - M\left({}^{56}_{26}Fe\right)\right]\ x931.5MeV$$

$$B.E. = \left[Z.m_H + (A-Z).m_n - M\left({}^{56}_{26}Fe\right)\right]\ x931.5MeV$$

$$= 492.2663MeV$$

$$\frac{B.E.}{A} = 8.79MeV$$

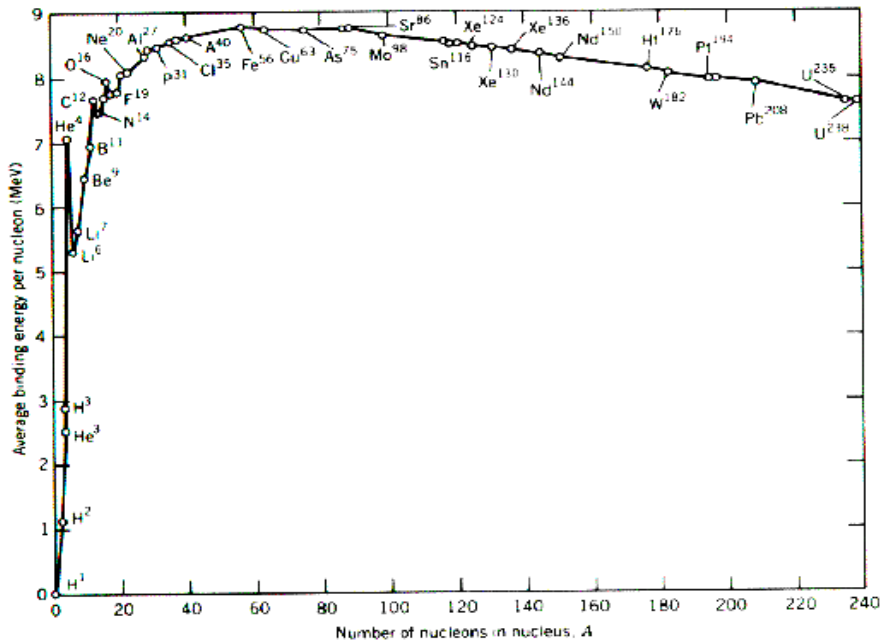
مثال: احسب الطاقة الرابطة لكل نيوكلون في ذره الكربون.

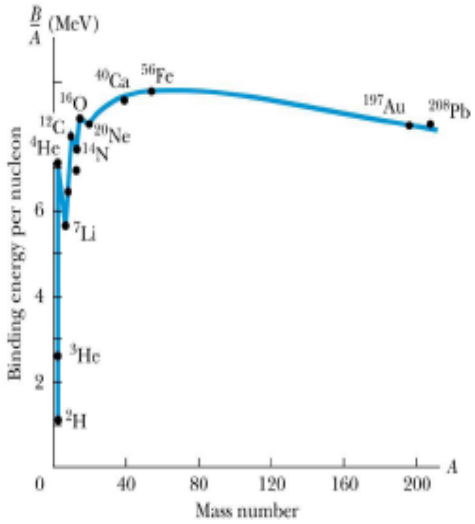
- تحتوي ذرة الكربون-12 على 6 بروتونات و6 نيوترونات لذلك فأن كتلتها تساوي:

$M = (6 \times m_p) + (6 \times m_n) = 12.095646\ u$

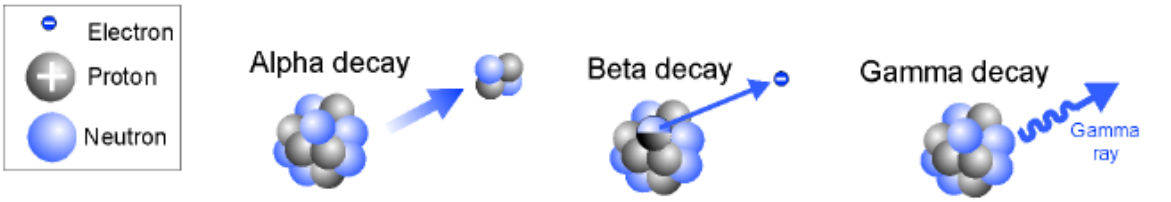
- كتلة النواة الفعلية هي: $M_{eff}\ (^{12}C) = 11.996706\ u$
- الفرق بين كتلة النواة ومجموع كتل مكونات النواة: $\Delta m = 0.09894\ u$
- مقدار الطاقة الرابطة: $E = \Delta m\ (u) \times 931.5 = \Delta\ m\ (u)\ C^2$
- طاقة الربط لكل نيوكلون : $B.E./A = 92.2\ MeV/12 = 7.68\ MeV$

، اكبر قيمة لها تكون عند العدد الكتلي 60، ثم (A)تزيد قيمة الطاقة الرابطة لكل نيوكلون بزيادة العدد الكتلي وذلك بسبب زيادة عدد البروتونات والنيوترونات أي زيادة قوى التنافر الكهربية التي تعاكس Aتقل بزيادة قوى الترابط (الجذب) النووية.





•تزيد قيمة الطاقة الرابطة لكل نيوكلون بزيادة العدد الكتلي (A)، اكبر قيمة لها تكون عند العدد الكتلي 60، ثم تقل بزيادة A وذلك بسبب زيادة عدد البروتونات والنيوترونات أي زيادة قوى التنافر الكهربية التي تعاكس قوى الترابط (الجذب) النووية.



Protons	Decrease by 2	Increase by 1	Unchanged
Neutrons	Decrease by 2	Decrease by 1	Unchanged

ط

أمثلة

مثال ١ احسب طاقة الترابط لنواة نظير الديتيريوم المكونة من بروتون واحد ونيوترون واحد. حيث أن كتلتها مقدرة بوحدات الكتلة الذرية تساوي ٢,٠١٢٥٤٧ .

$$\text{Mass deficiency} = 1\times 1.008665 + 1\times 1.007277 - 2.013547$$

(Mass deficiency ← نقص الكتلة داخل النواة ؛ 1.008665 ← نيوترون ؛ 1.007277 ← بروتون ؛ 2.013547 ← نواة)

$$= 2.395\times 10^{-3}\ \text{amu}$$

$$\therefore B.E. = 2.395\times 10^{-3}\times 931 = 2.229745\ \text{MeV}$$

ويكون نصيب كل جسيم من هذه الطاقة بمعدل (مقدار B.E. مقسوماً على عدد الجسيمات المكونة للنواة) وهو في هذه الحالة ٢ .

$$\therefore B.E.\ (\text{nucleon}) = 1.1148725\ \text{MeV}$$

nucleon ← نيوكلون ≡ نقصد به البروتون أو النيوترون

بلا شك أن النواة لأي نظير أو عنصر تزداد تماسكاً كلما زاد مقدار الترابط بين مكونات النواة أي ازداد مقدار طاقة الترابط لكل جسيم من جسيمات النواة والعكس صحيح.

ملاحظة: طاقة الترابط النووي الكلية هي مقدار الطاقة الذي ينطلق عند دمج مكونات النواة معاً لتكون نواة العنصر وهو نفس مقدار الطاقة اللازم لتفكيك النواة إلى مكوناتها الأصلية ليصبح كل منها حراً.

مثال ٢ احسب كتلة الإلكترون بدلالة وحدة الكتلة الذرية وبوحدة MeV .

∵ كتلة الإلكترون = ٩,١ × ١٠$^{-٣١}$ كجم

ووحدة الكتلة الذرية = ١,٦٦٠٠٠ × ١٠$^{-٢٧}$ كجم

∴ كتلة الإلكترون = $\left[\dfrac{٩,١\times ١٠^{-٣١}\ \text{كجم}}{١,٦٦٠٠٠\times ١٠^{-٢٧}\ \text{كجم}}\right]$ = ٥,٤٩٦٨ × ١٠$^{-٤}$ وحدة كتلة ذرية

= ٥,٤٩٦٨ × ١٠$^{-٤}$ × ٩٣١ = ٠,٥١١٧٥٤ مليون إلكترون فولت.

مثال ٢ إذا افترضنا أن نواة الراديوم-٢٢٦ كروية الشكل. فكم يبلغ نصف قطرها؟

$$\because R = 1.2\,A^{1/3} \rightarrow R = 1.2\,(226)^{1/3} = 7.31\times 10^{-15}\,m$$

$$= 7.31\ Fm$$

وتسمى وحدة قياس الأبعاد النووية بـ فيرمي Fermi وهي تساوي ١٠$^{-١٥}$ متر.

طاقات الربط

عندما تجتمع الجسيمات النووية مع بعضها في النواة، ترتبط مع بعضها بفعل القوة النووية. يحتاج الأمر كمية من الطاقة لنزع الجسيم النووي من النواة (طاقة الربط الخاصة به) (وهي تماثل طاقة تأيين الإلكترون في الذرة). أما الطاقة المطلوبة لفصل كل مكونات النواة عن بعضها فهي طاقة الربط الكلية للنواة (B.E.). إذا كان عدد الجسيمات النووية المكونة للنواة A، تكون الطاقة الوسيطة اللازمة لنزع أحد الجسيمات النووية B.E./A) وهي طاقة الربط للجسيم. عندما نرغب بنزع كل الجسيمات النووية، علينا أن نزود كل جسيم نووي بهذه الكمية من الطاقة. عندما نأتي بجسيمات نووية منفصلة ونكوّن نواة يتحرر من الطاقة ما يساوي هذه الكمية لكل جسيم نووي. يعني ذلك أن طاقة الربط الكلية B.E. تساوي الطاقة التي تتحرر عندما نشكل نواة بدءاً من جسيمات نووية منفردة. كلما كانت طاقة الربط أكبر، تحررت كمية من الطاقة أكبر عند تكوين النواة. إذا اعتبرنا أن طاقة كل جسيم نووي منفرد تطابق الصفر، تغدو إذ ذاك طاقة النواة المرتبطة سالبة القيمة وتساوي طاقة الربط الكلية بالقيمة المطلقة.

تعلمنا في فصل النسبية أن الطاقة تكافىء الكتلة. إذا فقدت الطاقة، يعني ذلك فقدان كتلة مكافئة. تساوي كمية الكتلة المفقودة Δm، كمية الطاقة المفقودة ΔE مقسومة على c^2 ذلك أن $E = mc^2$. نتوقع تبعاً لذلك أننا إذا جمعنا بروتوناً ونيوتروناً لتكوين ديوتيرون فإن كتلة الديوتيرون تكون أقل من مجموع كتلتي البروتون والنيوترون المنفردين. يصح هذا الأمر لكل نواة أخرى حيث تقل كتلتها عن مجموع كتل مكوناتها. تدعى الكتلة المفقودة: «نقص الكتلة» وتساوي $(B.E.)/c^2$. إذا قسنا كتلة النواة، يمكننا حساب نقص الكتلة بمقارنة هذه الكتلة بمجموع كتل مكوناتها. نحصل بذلك على طاقة الربط للنواة. بفرض أن m_X هي الكتلة الذرية للذرة ${}_Z X^A$ و m_H كتلة ذرة الهيدروجين (بروتون وإلكترون) يكون لدينا:

$$\Delta m = Z(m_H) + (A - Z)(m_n) - m_X \qquad \text{لذرة } {}_Z X^A \qquad (13.18\text{أ})$$

لنلاحظ أننا إذا ضمنّا كتلة إلكترون في m_H يصبح لدينا Z كتلة إلكترون و Z كتلة بروتون في الحد الأول من الطرف الأيمن للمعادلة. نظراً لأن m_X كتلة ذرية فإنها تحتوي Z من الإلكترونات فيها وعندما نطرح m_X يبقى الفرق في الكتلة بين الجسيمات النووية (Z بروتون و $(A - Z)$ نيوترون وكتلة النواة المجردة). [نهمل هنا فرق الكتلة الضئيل المعزو إلى طاقات الربط الصغيرة للإلكترونات].

$$\text{B.E.} = \Delta m(c^2) \qquad (13.18\text{ب})$$

نستطيع قياس طاقة الربط بشكل منفصل عن طريق التجربة بتحديد كمية الطاقة اللازمة لفصل الجسيمات النووية عن بعضها في النواة. إذا قمنا بهذه التجربة، نحصل على تطابق ممتاز.

المسألة 14.18. تساوي الكتلة الذرية للنيوترون 1.0086649 u، والكتلة الذرية للهيدروجين ${}_1H^1$ (بروتون وإلكترون) 1.0078250 u. احسب نقص الكتلة للذرات التالية ذات الكتل المبينة.

(أ) ${}_1H^2$، بكتلة 2.014102 u.

(ب) ${}_2He^3$، بكتلة 3.016029 u.

(ج) ${}_2He^4$، بكتلة 4.002603 u.

(د) ${}_6C^{12}$، بكتلة 12.00000 u.

(هـ) ${}_{26}Fe^{57}$، بكتلة 56.935396 u.

(و) ${}_{92}U^{238}$، بكتلة 238.050786 u.

الحل

(أ) نحصل على نقص الكتلة Δm بجمع كتل كل المكونات وطرح كتلة النواة بعد ذلك. من أجل ${}_1H^2$ يساوي المجموع $1(m_H) + 1(m_n) = 1.0078250 + 1.0086649 = 2.0164899$. هكذا يكون نقص الكتلة
$2.0164899 - 2.014102 = 0.002388$ u.

(ب) نطبق نفس طريقة الجزء (أ) فنحصل على $\Delta m = 1(1.0086649) + 2(1.0078250) - 3.016029 = 0.008286$ u

(ج) من جديد، $\Delta m = 2(1.0086649) + 2(1.0078250) - 4.002603 = 0.030377$ u

(د) $\Delta m = 6(1.0086649) + 6(1.0078250) - 12.000000 = 0.098939$ u

(هـ) $\Delta m = 31(1.0086649) + 26(1.0078250) - 56.935396 = 0.536666$ u

(و) $\Delta m = 146(1.0086649) + 92(1.0078250) - 238.050786 = 1.934189$ u

المسألة 15.18. عيّن الطاقة الرابطة للجسيم النووي مقدرة بالإلكترون فلط للحالات المختلفة في المسألة 14.18.

الحل

(أ) تساوي الطاقة الرابطة بالجول $(\Delta m)c^2$ حيث Δm بالكيلوغرام. بفرض أن $\Delta m = 1$ u، تكون الطاقة الرابطة $(1.661 \times 10^{-27}\ \text{kg})(9.0 \times 10^{16}\ \text{m}^2/\text{s}^2) = (1.493 \times 10^{-10}\ \text{J})/1.602 \times 10^{-19}\ \text{eV} = 932\ \text{MeV}$ (استخدمنا قيم أدق لكل من c^2 و J/eV مقارنة مع ما فعلناه سابقاً). هكذا يكون التحويل من كتلة مقدرة بالوحدة u إلى MeV: 932. كان نقص الكتلة للذرة $_1H^2$: 0.002388 u وهذا يقابل طاقة رابطة قدرها $(0.002388\ \text{u})(932\ \text{MeV/u}) = 2.226\ \text{MeV}$. نظراً لوجود جسيمين نويين في هذه النواة، تكافىء الطاقة الرابطة للجسيم النووي 1.11 MeV.

(ب) هنا يساوي نقص الكتلة 0.008286 u، وهو يعطي الطاقة الرابطة $932(0.008286) = 7.72$ MeV، والطاقة الرابطة للجسيم النووي $7.72/3 = 2.57$ MeV.

(ج) هنا يساوي نقص الكتلة 0.030377 u، وهو يعطي الطاقة الرابطة $932(0.030377) = 28.1$ MeV، والطاقة الرابطة للجسيم النووي $28.31/4 = 7.07$ MeV.

(د) هنا يساوي نقص الكتلة 0.098939 u، وهو يعطي الطاقة الرابطة $932(0.098939) = 92.21$ MeV، والطاقة الرابطة للجسيم النووي $92.21/12 = 7.68$ MeV.

(هـ) هنا يساوي نقص الكتلة 0.536666 u، وهو يعطي الطاقة الرابطة $932(0.0536666) = 500.02$ MeV، والطاقة الرابطة للجسيم النووي $500.02/57 = 8.77$ MeV.

(و) هنا يساوي نقص الكتلة 1.934195 u، وهو يعطي الطاقة الرابطة $932(1.934189) = 1802.66$ MeV، والطاقة الرابطة للجسيم النووي $1802.66/238 = 7.57$ MeV.

المسألة 16.18. إن الطاقة الرابطة للجسيم النووي في الذرة $_{82}Pb^{208}$ هي 7.93 MeV للجسيم النووي. ما هي الكتلة الذرية لهذه الذرة.

الحل

تساوي الطاقة الرابطة الكلية للذرة $208(7.93) = 1649.44$ MeV. يعني ذلك نقصاً بالكتلة يكافىء $1649.44/932 = 1.76979$ u. باستخدام المعادلة (13.18 أ) نخلص إلى كتلة الرصاص

$$m = 126(1.0086640) + 82(1.0078250) - 1.76979 = 207.964\ \text{u}.$$

المسألة 17.18. استخدم المعلومات المعطاة في المسألة 14.18 للنظير $_1H^2$. احسب انطلاقاً من اعتبارات الطاقة التواتر الأصغري للفوتون الضروري لتفريق النيوترون عن البروتون. تدعى هذه العملية التحلل الضوئي.

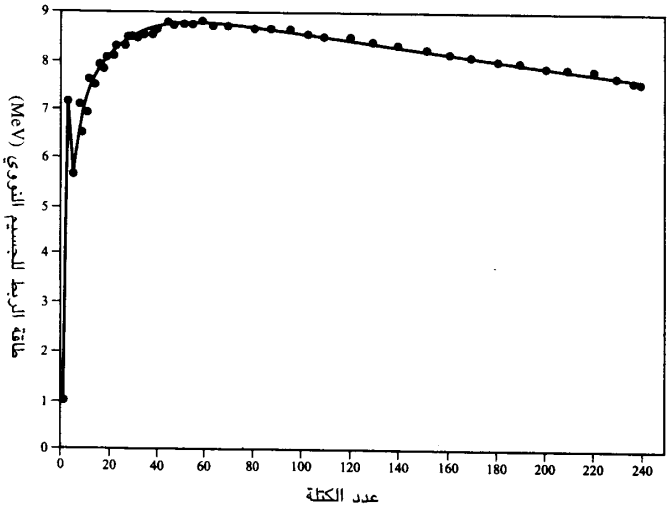
الحل

تساوي الطاقة الضرورية لتفريق هذه النواة طاقة الربط الخاصة بها. نحسب طاقة الربط [المسألة 16.18 (أ)] على أنها 2.23 MeV. يعني ذلك أن الطاقة الأصغرية للفوتون تكافىء 2.23 MeV. (كي تنحفظ كمية الحركة أيضاً، يجب أن تزيد الطاقة قليلاً عن هذه القيمة). إن الفوتون ذا الطاقة 2.23 MeV له تواتر يعادل

$$f = E/h = (2.23 \times 10^6\ \text{eV})(1.6 \times 10^{-19}\ \text{J/eV})/(6.625 \times 10^{-34}\ \text{J . s}) = 5.39 \times 10^{20}\ \text{Hz}.$$

أوضحت المسائل السابقة الطريقة التي يُمكن أن نحصل بواسطتها على معلومات تكشف عن قوة ارتباط الجسيمات النووية داخل النواة. إن كانت الطاقة الرابطة كبيرة، فلا شك أن طاقة كبيرة قد تحررت عند تكوين النواة وأدى ذلك إلى ارتباط شديد للجسيمات

النووية. على العكس، إذا كانت الطاقة الرابطة صغيرة، تكون الجسيمات النووية هشة الارتباط. يُمكن أن تحول النواة إلى نواة أخرى بطاقة ربط أكبر بما يعني تحرير المزيد من الطاقة. كي نبحث هذه الإمكانية من المفيد أن نوقع الطاقة الرابطة للجسيم النووي بدلالة A وأن نحلل النتيجة. يعطي الشكل 18-16 مخطط (B.E.)/A بدلالة A. نلاحظ وجود قيمة أعظمية لِـ (B.E.)/A تساوي 8.77 MeV للجسيم النووي تتحقق من أجل Fe^{57}. تضم هذه النواة الخاصة جسيمات نووية مربوطة إلى بعضها بشدة لا يضاهيها ارتباط الجسيمات في أية نواة أخرى. إن كان على الجسيمات النووية في النوى الأخرى أن تعيد تنظيم نفسها للتحول إلى Fe^{57} فلا بد أن تطلق المزيد من الطاقة إلى أن تزيد طاقة الربط حتى 8.77 MeV للجسيم النووي. يُمكن لهذا أن يحدث إذا اندمجت العناصر الخفيفة مع بعضها ($A < 57$) لتشكيل نوى بقيم أكبر لِـ A عبر عملية تعرف بالاندماج. إن هذا هو مصدر طاقة الشمس والنجوم الأخرى وكذلك القنبلة الهيدروجينية. يأمل الباحثون أن تكون هناك إمكانية في المستقبل لاستخدام هذا المصدر على الأرض ضمن سياق منضبط بدمج ذرات الهيدروجين لتشكيل ذرات الهليوم ذات طاقة الربط الأكبر. نستطيع تحرير الطاقة أيضاً بتحويل النوى الثقيلة (مثل الأورانيوم) إلى نوى أخف تمتلك قيماً أكبر للنسبة (B.E.)/A با يؤدي إلى تحرير الطاقة. تدعى هذه العملية الانشطار وهي مصدر الطاقة في المفاعلات النووية والقنابل الذرية.



الشكل 18-16

المسألة 18.18. تمتلك الذرة $_2He^4$ طاقة رابطة للجسيم النووي تساوي 7.0 MeV/A، بينما الطاقة المقابلة في الذرة H^2، (الديوتيريوم) هي 1.11 MeV/A. إذا دمجنا ذرتي ديوتيريوم لتشكيل ذرة He^4، كم تبلغ كمية الطاقة المحررة.

الحل

قبل الاندماج كانت طاقة الربط الكلية 2.22 MeV = 2(1.1). تغدو طاقة الربط بعد الاندماج 28 MeV = 4(7.0). يعني ذلك أن طاقة إضافية قدرها 25.8 MeV ≈ (2.22 − 28) قد تحررت أثناء الاندماج.

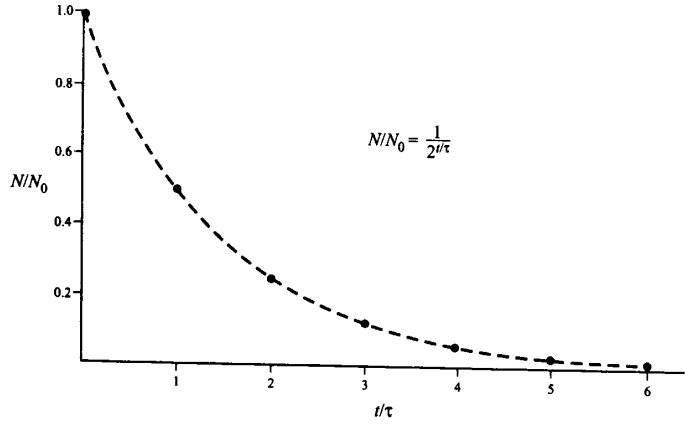
النشاط الإشعاعي

بحثنا حتى الآن خصائص النوى المستقرة. توجد أعداد من النوى، بعضها ذات منشأ طبيعي، تتسم بعدم الاستقرار. إنها تتحول إلى نوى أخرى عبر مراحل محددة. نشرح في هذه الفقرة الميزات العامة للتحلل الإشعاعي، كما نتطرق في الفقرة التالية إلى خصائص أنواع معينة من التحلل.

يتسم كل تحلل نووي خاص بنصف حياة τ. إنه الزمن المتوسط اللازم لتحلل نصف النوى. على الرغم من أن أحداً لا يدري أي

شيء عن الذرة التي تجنح نواتها إلى التحلل في لحظة معينة فإن ما يبقى من النوى دون تحلل بعد مضي الفترة τ هو نصف عددها الأصلي N_0، أي $N_0/2$. إذا انتظر الباحث لفترة إضافية τ، تتحلل نصف النوى المتبقية ويتخلف منها دون تحلل $(N_0/2)/2 = N_0/2^2$. بعد فترة أخرى τ يبقى من النوى $N_0/2^3$. بصورة عامة، يبقى من النوى $N_0/2^m$ بعد مضي فترة قدرها $m\tau$، يتضح في الشكل 17-18 ويتبين أن النسبة N/N_0 تتناقص تناقصاً أسياً وفق $2^{-(t/\tau)}$. نتحول إلى الأس الطبيعي e، فنحصل على:

$$N = N_0 e^{-\lambda t}, \quad \text{حيث} \quad \lambda = (\ln 2)/\tau. \tag{4.18}$$



الشكل 17-18

إنه تحلل أسي، يساوي ثابت التحلل فيه λ. إن هناك طريقة أساسية أخرى للوصول إلى نفس هذه المعادلة. نفرض أن عدد الجسيمات التي تتحلل في غضون فترة قصيرة Δt (قصيرة بالمقارنة مع نصف الحياة) يتناسب مع عدد الجسيمات الموجودة في تلك الفترة. نستطيع إذ ذاك أن نكتب

$$\Delta N/\Delta t = -\lambda N \tag{15.18}$$

حيث λ ثابت موجب. أما الإشارة السالبة فتعني أن N يتناقص. نستطيع حل هذه المعادلة بتطبيق طرائق التحليل الرياضي. أما النتيجة فهي المعادلة (14.18). تمثل الكمية $|\Delta N/\Delta t|$ عدد أحداث التحلل في الثانية عند أية لحظة. تدعى هذه الكمية فعالية المادة ذات النشاط الإشعاعي وتقاس بوحدة البيكريل (Bq) التي تساوي تحللاً واحداً في الثانية. إن هناك وحدة أكثر شيوعاً للفعالية هي الكوري (Ci) وتساوي 3.70×10^{10} Bq.

المسألة 19.18. يساوي ثابت التحلل لإحدى المواد $4.2 \times 10^3\ s^{-1}$. يبدأ التحلل بوجود 3.0×10^7 ذرة.

(أ) ما هو نصف الحياة لهذه المادة؟

(ب) ما هي الفعالية الابتدائية للمادة؟

(ج) كم يبقى من الذرات بعد مضي 1.2×10^{-3} s؟

(د) ما هي فعالية العينة بعد مضي 1.2×10^{-3} s؟

الحل

(أ) نجد باستخدام المعادلة (14.18) أن $\tau = (\ln 2)/\lambda = 0.693/4.2 \times 10^3 = 1.65 \times 10^{-4}$ s

(ب) نطبق المعادلة (15.18)، $\Delta N/\Delta t = -\lambda N$، فنحصل على الفعالية

$$|\Delta N/\Delta t| = 4.2 \times 10^3 (3.0 \times 10^7) = 1.26 \times 10^{11}\ \text{Bq} = 3.4\ \text{Ci}$$

(ج) نستخدم المعادلة (14.18)، $N = N_0 e^{-\lambda t}$، فنجد أن

$$N = 3.0 \times 10^7 \ \exp\left(-4.2 \times 10^3 \times 1.2 \times 10^{-3}\right) = 3.0 \times 10^7 \ \exp(-5.04) = 1.94 \times 10^5 \text{ atoms}$$

(د) نطبق المعادلة (15.18) $\Delta N/\Delta t = -\lambda N$، فنحصل على الفعالية

$$|\Delta N/\Delta t| = 4.2 \times 10^3 (1.94 \times 10^5) = 8.16 \times 10^8 \text{ Bq} = 0.022 \text{ Ci}$$

المسألة 20.18. يوجد في إحدى العينات 5.6×10^8 من الجسيمات يبقى منها بعد 25 s، 0.70×10^8 جسيماً. ما هو نصف حياة هذا التحلل.

الحل

نحسب أولاً $N/N_0 = 0.70 \times 10^8/5.6 \times 10^8 = 1/8$. توجد طريقتان الآن لمتابعة حل المسألة. نلاحظ أولاً أن $1/8 = 1/2^3$. يعني ذلك أن ثلاثة أنصاف حياة قد مضت. إذن $3\tau = 25$، بالتالي $\tau = 25/3 = 8.33$ s . توظف الطريقة الثانية المعادلة (14.18)، $N/N_0 = e^{-\lambda t}$، $0.125 = e^{-\lambda t}$، $\ln(0.125) = -\lambda t = -2.079$، $\tau = (\ln 2)/\tau = 0.832 = 2.079/25$، $\tau = 8.33$ s

المسألة 21.18. تحوي عينة 6.4×10^7 من الجسيمات. يساوي نصف الحياة 3.5 s.

(أ) كم يبلغ ثابت التحلل في هذا التحلل.

(ب) بعد أية فترة من الزمن يبقى من الجسيمات ما يساوي 1.3×10^7 جسيماً.

(ج) ما هي الفعالية بعد مضي 10 s.

الحل

(أ) نعرف أن $\lambda = (\ln 2)/\tau$. إذن $\lambda = 0.693/3.5 = 0.198 \text{ s}^{-1}$.

(ب) نستخدم المعادلة (14.18)، $N = N_0 e^{-\lambda t}$، فنحصل على $N = 1.3 \times 10^7 = 6.4 \times 10^7 \exp(-0.198t)$. بالتالي $\exp(-0.198t) = 0.203$، $\ln(0.203) = -1.59 = -0.198t$، $t = 8.05$ s .

(ج) الفعالية $|\Delta N/\Delta t| = +\lambda N$. نحسب أولاً $N = N_0 \ \exp(-\lambda t) = 6.4 \times 10^7 \ \exp(-0.198 \times 10) = 8.84 \times 10^6$. إذن

$$|\Delta N/\Delta t| = 0.198(8.84 \times 10^7) = 1.75 \times 10^6 \text{ Bq} = 4.73 \times 10^{-5} \text{ Ci} = 47.3 \ \mu\text{Ci}$$

يفيد العلماء من النشاط الإشعاعي الطبيعي في التأريخ للعينات الجيولوجية أو الآثارية. إذا فرضنا أننا نعرف التركيب الابتدائي للمادة بدلالة النوى الموجودة، وكانت بعض النوى مشعة، نستطيع تقدير عمر العينة بتحديد تركيبها في الوقت الحاضر. يُعطى العمر بالمعادلة $N/N_0 = \exp(-\lambda t)$، أو $t = \ln(N_0/N)/\lambda$. لسوء الحظ، إننا لا نعرف N_0 على وجه التحديد. تبين المسألة التالية ما الذي نستطيع أن نفعله.

المسألة 22.18. إن نظير الفحم C^{14} مشع ويساوي نصف حياته 5730 سنة، أما C^{12} فهو مستقر. كانت نسبة C^{12} إلى C^{14} في البداية 8.3×10^{11}. زادت النسبة بعد مضي الفترة t فغدت 9.1×10^{12}. حدّد هذه الفترة t.

الحل

نفرض أن N_{12} هو عدد النوى C^{12} التي كانت موجودة في الأصل. بما أن هذا النظير مستقر، يبقى نفس عدد النوى بعد مضي الفترة t. نستخدم نسبتي C^{12} إلى C^{14} للحظتي البداية والنهاية، فنجد أن العدد الابتدائي N_0 للنوى C^{14} كان $N_{12}/8.3 \times 10^{11}$، وأن العدد النهائي N للنوى C^{14} الموجودة هو $N_{12}/9.1 \times 10^{12}$. إذن $N/N_0 = (8.3 \times 10^{11})/(9.1 \times 10^{12}) = 0.0912$. لكن لدينا أن $N/N_0 = \exp(-\lambda t)$ أيضاً

$$\lambda = 0.693/\tau = 0.693/5730 \text{ y} = 1.210 \times 10^{-4} \text{y}^{-1} \text{ . بالتالي}$$

$$\ln(0.0912) = \lambda t \rightarrow -2.39 = -1.21 \times 10^{-4} t \quad \text{أو} \quad t = 19{,}790 \text{ y}$$

تفسح هذه الطريقة المجال لتحديد تاريخ المواد العضوية على أساس الافتراضات التالية. (1) بقيت النسبة C^{12}/C^{14} ثابتة في الغلاف الجوي على مدى التاريخ الجيولوجي. (2) عندما تنمو المادة العضوية وتمتص الفحم، تساوي النسبة الممتصة نفس النسبة المتواجدة في البحر أو الهواء. (3) عندما تموت المادة العضوية (شجرة مثلاً) يتوقف إصدار وامتصاص الفحم بشكل كيميائي ويبقى المصدر الوحيد

- انبعاث جسيمات ألفا:

Alpha decay $\quad {}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$

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

- Q (MeV)- طاقة التفكك = $[M_X - (M_Y+M_\alpha)](u) * 931.5$

- انبعاث جسيمات بيتا سالبة:

N → P + B- (بيتا سالبة)+ ν' (ضد النيوترينو)

Beta decay (e^-) $\quad {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^- + \bar{\nu}$

$$ {}^{14}_{6}C \rightarrow {}^{14}_{7}N + B^- + \bar{\upsilon} $$

Q (MeV)- طاقة التفكك $=[M_X-(M_Y+M_e)](u)*931.5$

- انبعاث جسيمات بيتا موجبة:

P → N + B+ (بيتا موجبة)+ ν (النيوترينو)

Beta decay (e^+) $\quad {}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^+ + \nu$

$$ {}^{13}_{7}N \rightarrow {}^{13}_{6}C + B^+ + \upsilon $$

Q (MeV)- طاقة التفكك $=[M_X-(M_Y+M_e)](u)*931.5$

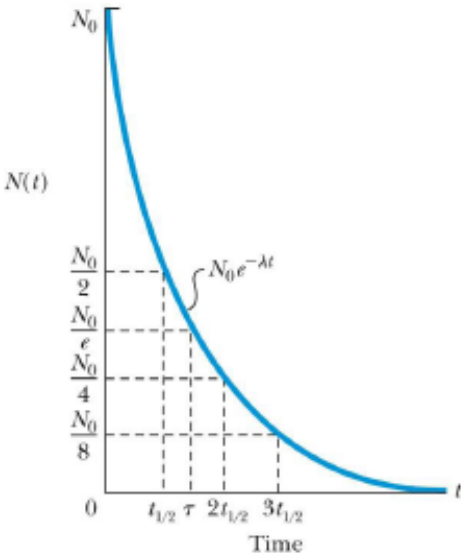
- انبعاث اشعة جاما:

بعد التفكك الإشعاعي وانبعاث جسيمات ألفا أو بيتا، قد تحتوي النواة الناتجة من التفكك على طاقة زائدة تكون النواة في حالة أثارة. لكي تستقر تتخلص النواة من الطاقة الزائدة بانبعاث أشعة جاما وهي موجات كهرومغناطيسية.

Gamma decay $\quad {}^{A}_{Z}X^* \rightarrow {}^{A}_{Z}X + \gamma$

10-14 عمر النصف الفيزيائي: $T_{1/2}$

- الزمن اللازم لتفكك نصف عدد النوى المشعة



$$ \frac{N_o}{2} = N_0 e^{-\lambda T_{1/2}} $$

$$ \frac{1}{2} = e^{-\lambda T_{1/2}} $$

$$ 2 = e^{\lambda T_{1/2}} $$

$$ \ln 2 = \lambda T_{1/2} \Rightarrow 0.693 = \lambda T_{1/2} $$

$$ T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda} $$

مسائل في الفيزياء النووية حول الإضمحلال الإشعاعي

1 إذا كانت الفعالية الإشعاعية لواحد ميلي جرام (1mg) من نظير الراديوم ^{226}Ra تقدر بـ 3.69×10^{7} إضمحلال في الثانية. فما هي فترة عمر النصف وثابت الإضمحلال لهذا العنصر المشع؟

الحل نحسب عدد الذرات (النوى) الموجودة في العينة باستخدام القانون

$$n = \frac{m \times N_A}{A}$$

عدد الذرات

m الكتلة بالجرام

N_A عدد أفوجادرو

A الوزن الذري

$$\therefore n = \frac{10^{-3} \times 6.023 \times 10^{23}}{226} = 2.66\times10^{18} \text{ nucleus}$$

* وحيث أن الفعالية الإشعاعية = عدد الذرات × ثابت الإضمحلال

$$A = \lambda n$$

$$\therefore A = \lambda n \rightarrow \lambda = \frac{A}{n} = \frac{3.69\times10^{7}}{2.66\times10^{18}} = 1.387\times10^{-11} \text{ Sec}^{-1}$$

* ونحسب فترة عمر النصف $T_{\frac{1}{2}}$ باستخدام العلاقة

$$\lambda = \frac{\ln 2}{T_{1/2}} \rightarrow T_{1/2} = \frac{\ln 2}{\lambda}$$

$$\therefore T_{1/2} = \frac{0.693}{1.387\times10^{-11}} = 4.997\times10^{10} \text{ sec}$$

$$= \frac{4.997\times10^{10}}{60\times60\times24\times365.25} = 1583.4 \text{ year.}$$

365.25 ← متوسط عدد أيام السنة

٢) احسب كتلة عينة من نظير الكوبالت 60 ($^{60}_{27}Co$) ، كانت كفاءتها الإشعاعية عند التحضير كوري واحد. فترة عمر النصف لـ $^{60}_{27}Co$ تساوي 5.27 سنة .

الحل

∵ الكفاءة الإشعاعية (A) = عدد الأنوية × ثابت الاضمحلال

ونرمز لكفاءة الإشعاعية عند التحضير (أي عند زمن يساوي صفر) بالرمز A_0

$$\therefore A_0 = \lambda N_0 = \frac{\ln 2}{T_{1/2}} N_0$$

$$1 \times 3.7 \times 10^{10} = \frac{0.693}{5.27 \times 60 \times 60 \times 24 \times 365.25} \times N_0$$

$$\therefore N_0 = \frac{3.7 \times 10^{10}}{4.167 \times 10^{-9}} = 8.88 \times 10^{18} \text{ nuclei}$$

$$N_0 = \frac{m \times N_A}{A} =$$

$$\therefore m = \frac{N_0 \times A}{N_A} = \frac{8.88 \times 10^{18} \times 60}{6.023 \times 10^{23}} = 8.846 \times 10^{-4} \text{ gm}$$

$$\simeq 0.88 \text{ mg} .$$

٢) عينة من كوبالت-60 (^{60}Co) وزنها عند التحضير 1mg . إحسب ثابت الإضمحلال (التفكك) والكفاءة الإشعاعية بوحدة الكوري والبكريل إذا كانت فترة عمر النصف تساوي 5.27 year ، احسب الكفاءة الإشعاعية بعد مرور عشر سنوات من تحضير العينة .

الحل

* ثابت الإضمحلال (λ) يتم حسابه بـ sec^{-1} ولذلك نقوم بتحويل فترة عمر النصف من وحدة السنة إلى ثانية

$$T_{1/2} = 5.27 \times 365.25 \times 24 \times 60 \times 60$$

$$= 1.66 \times 10^{8} \text{ sec}$$

$$\because \lambda = \frac{\ln 2}{T_{1/2}} = \frac{0.693}{1.66 \times 10^{8}} = 4.17 \times 10^{-9} \text{ sec}^{-1}$$

* الكفاءة الإشعاعية عند تحضير العينة A_0

$$\because A_0 = \lambda N_0 = \lambda \times \frac{m \times N_A}{A}$$

A = الوزن الذري

$$= 4.17 \times 10^{-9} \times \frac{1 \times 10^{-3} \times 6.023 \times 10^{23}}{60}$$

$$= 4.185985 \times 10^{10} \text{ Bq}$$

$$= 1.13 \text{ Ci} \quad \leftarrow \quad 1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$$

* بعد إنقضاء عشرة سنوات من تحضير العينة ، يتناقص عدد الأنوية الناتجة فيكون طبقاً للمعادلة $N = N_0 e^{-\lambda t}$ ← $\lambda N = \lambda N_0 e^{-\lambda t}$

$$\therefore A = A_0 e^{-\lambda t}$$

$$\therefore A = 1.13 \, e^{-\frac{0.693}{5.27} \times 10}$$

$$= 0.3 \text{ Ci}$$

ملاحظة : بدلاً من تحويل فترة عمر النصف والفترة المنقضية منذ التحضير من سنة إلى ثانية ، وبالتالي وجود عوامل مشتركة فى البسط والمقام لأس e . نستخدم السنة مباشرة لكل من t و $T_{1/2}$.

٤) عينة من خام البوتاسيوم ذات كتلة 46.3 mg ونشاط إشعاعي يقدر بـ 1.5 Bq ، فإذا كان مصدر إشعاع β للعينة هو نظير البوتاسيوم ^{40}K ونسبته في العينة 0.012 % . أحسب فترة عمر النصف للبوتاسيوم-٤٠ .

الحل

طالما فترة عمر النصف ، لابد من معرفة عدد الأنوية الموجودة بالعينة .

وحيث أن نسبة وجود البوتاسيوم ٤٠ في العينة يساوي 0.012% فإن كتلة هذا النظير تساوي

$$m_{^{40}K} = \frac{0.012}{100} \times 46.3 \times 10^{-3} = 5.556 \times 10^{-6} \text{ gm}$$

∴ عدد أنوية البوتاسيوم ٤٠ في العينة

$$N = \frac{5.556 \times 10^{-6} \times 6.023 \times 10^{23}}{40}$$

$$= 8.36 \times 10^{16} \text{ nuclei}$$

* بإستخدام الكفاءة الإشعاعية وعدد الأنوية ، يمكن حساب ثابت الإضمحلال ومنه فترة عمر النصف .

$$\because A = \lambda N \rightarrow 1.5 = \lambda \times 8.36 \times 10^{16}$$

$$\therefore \lambda = 1.79 \times 10^{-17} \text{ sec}^{-1}$$

$$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda} = \frac{0.693}{1.79 \times 10^{-17}} = 3.87 \times 10^{16} \text{ sec}$$

$$= 1.226 \times 10^{9} \text{ year}$$

٥ احسب كتلة نظير السترانشيوم ^{90}Sr ذات نشاط إشعاعي مقداره جرام واحد من نظير الكوبالت (٦٠) علماً بأن

$T_{1/2}|_{Cobalt} = 5.27$ year

$T_{1/2}|_{Sr} = 28.1$ year.

الحل عدد الذرات في جرام واحد من الكوبالت

$$N_o = \frac{1 \times 6.023 \times 10^{23}}{60} = 1.00 \times 10^{22} \text{ nuclei}$$

وبالتالي فإن الفاعلية الإشعاعية لهذه العينة

$$A_o = \lambda N_o = \frac{0.693}{5.27 \times 365.25 \times 24 \times 60 \times 60} \times 1 \times 10^{22}$$

$$= 4.167 \times 10^{13} \text{ Bq}$$

$$= 1.126 \times 10^{3} \text{ Ci}$$

وحيث أن الفاعلية الإشعاعية للنظيرين متساوية $A_{Co} = A_{Sr}$

$$\therefore \lambda_{Co} N_{Co} = \lambda_{Sr} N_{Sr}$$

$$\therefore N_{Sr} = \frac{A_{Co}}{\lambda_{Sr}} = \frac{4.167 \times 10^{13}}{0.693/(28.1 \times 365.25 \times 24 \times 3600)}$$

$$= 5.332 \times 10^{22} \text{ nuclei}$$

$$\because N = \frac{m \times N_A}{A} \rightarrow m = \frac{N \times A}{N_A}$$

$$\therefore m = \frac{5.332 \times 10^{22} \times 90}{6.023 \times 10^{23}}$$

$$= 7.967 \text{ gm}$$

[٦] إحسب حجم وكتلة الرادون-٢٢٢ المتوازن إشعاعياً مع الراديوم-٢٢٦

حيث فترة عمر النصف للرادون ← $T_{1/2}\big|_{Rn} = 3.825$ day

" " " للراديوم ← $T_{1/2}\big|_{Ra} = 1622$ year

كثافة الرادون (وهو غاز) ← $\rho_{Rn} = 9.37\times10^{-3}\ Kg/m^3$

الحل: لابد أولاً من تحديد نوع التوازن هل هو أبدي أم مؤقت (مرحلي) لأن ذلك سيحدد صيغة المعادلة التي سيتم تطبيقها. ويتم تحديد نوع التوازن بحساب (أو مقارنة) فترتي عمر النصف. من الملاحظ أن $T_{1/2}\big|_{Ra} \gg T_{1/2}\big|_{Rn}$

وهذا يدل على أن التوازن الإشعاعي من النوع الأبدي ولذلك نجد أن

$$A_1 = A_2$$

A_1 ← للراديوم، A_2 ← للرادون

$$\therefore \lambda_1 N_1 = \lambda_2 N_2 \rightarrow \frac{\ln 2}{T_{1/2}\big|_1} N_1 = \frac{\ln 2}{T_{1/2}\big|_2} N_2$$

$$\therefore T_2 N_1 = T_1 N_2$$

$$\therefore T_2 \times \frac{m_1 \times N_A}{A_{226}} = T_1 \frac{m_2 \times N_A}{A_{222}}$$

$$\therefore m_2 = \frac{T_2 \times m_1 \times A_{222}}{T_1 \times A_{226}} = \frac{3.825 \times 1 \times 222}{1622 \times 365.25 \times 226}$$

$$= 6.342 \times 10^{-6}\ gm$$ ← كتلة الرادون

وحيث أن الكتلة = الحجم × الكثافة

$$\rho \times V = m$$

$$\therefore V_2 = \frac{m_2}{\rho_2} = \frac{6.342 \times 10^{-6}}{9.37 \times 10^{-3}}$$

$$= 6.768 \times 10^{-4}\ m^3$$ *

Refrences

1- An Introduction to Radiation Protection **Seventh Edition**
Alan Martin , Sam Harbison, Karen Beach, Peter Cole, CRC Press , Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300, Boca Raton, FL 33487-2742

2- ICRP Publication 60: *1990 Recommendations of the Interna- tional Commission on Radiological Protection.* New York: Pergamon Press; 1991.

3- Physics and Radiobiology of Nuclear Medicine, Gopal B. Saha, Third Edition, 2006

4- Concepts Of Nuclear Physics , Bernard L.Cohen (1984).

5- Nuclear Physics ,Addison Wesley , Kaplan , I.(1979).

6- 4- Nuclei and Particles , Segre , E.Benjam In (1965).

7- Atoms, Radiation and radiation protection *J. E. turner, 1995*

8- Essentials of Nuclear Medicine Physics and Instrumentation. Rachel A. Powsner, Matthew R. Palmer, Edward R. Powsner, THIRD EDITION A John Wiley & Sons, Ltd., Publication 2013

9- الفيزياء النووية ، د. احمد الناغى ، دار الفكر العربى (2005). -

10- الوقاية من الإشعاعات المؤينة, د. بهاء الدبن حسين معروف, 1989

11- الوقاية الإشعاعية المبادئ والتطبيقات د / مصطفي محمد عبدالمهدي المجالي

12- مبادىء الاشعاعات المؤينة والوقاية منها ا د/ محمد فاروق احمد ا د/ احمد بن محمد السريع

13- محاضرات ا .د/ صالح محمد متولى

14- الوكالة الدولية للطاقة الذرية

https://www.iaea.org/ar/almawadie/alnazayir-almushiea

Goodwin PN: Radiation safety for patients and personnel. In: Freeman LM, ed. *Freeman and Johnson's Clinical Radionuclide Imaging.* 3rd ed. Philadelphia: WB Saunders Co;1984: 320.

Tatjana Jevremovic, Nuclear Principles in Engineering, Springer, (2009).

Dan Gabriel Cacuci, Handbook of Nuclear Engineering, Springer (2010).

Jean-Louis Basdevant, Michel Spiro, James Rich, Fundamentals In Nuclear Physics , From Nuclear Structure to Cosmology, Springer (2005).

Michael F. L'Annunziata, Radioactivity: Introduction and History, Elsevier B.V (2007).

تقرير عن استخدامات النظائر المشعة
فى الطب والزراعة والصناعة

اسم الطالب :.....

الرقم الجامعى :.....

الفرقة :.....

الشعبه: .....

اشراف

د/ عادل جادالكريم عبادي محمد

أستاذ الفيزياء الإشعاعية والنووية المساعد

الفصل الدراسي الثاني - العام الجامعي

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