

Chapter 1:

Brief Introduction to Radioactivity

Natural radioactivity is a spontaneous and self-disruptive activity exhibited by a number of heavy elements occurring in nature. The word spontaneous means by its own or by sheer out of nature of the element and self-disruptive means that the element disintegrates itself i.e. no external provocation influences the emission. Radioactivity is, therefore, the property by virtue of which a heavy element disintegrates itself without being forced by any external agent to do so. (Winner Science 2013) After the discovery of radioactivity in 1896 by a French Physicist, Henry Becquerel (Allisy, 1996), the science of radioactivity has been extensively studied. Radionuclides are the sources of radioactivity and emit nuclear radiations which have become a part of our daily lives. The most common forms of ionizing radiation are alpha particles, beta particles and gamma rays (Lilley, 2001). Radiation can arise not only from natural radionuclides, but it can also be from man-made sources. The properties of radiations have been widely applied to various purposes such as medicine, biology, industry, agriculture, and electric power generation (Eisenbud, and Gesell, 1997). As a result of the applications of radiation, humans can be exposed to the radiation emitting from different radioactive sources depending upon their activities and surroundings (Klement, 1982). However, not all of the population is subjected to all the various sources of radiation exposure. For instance, patients who are treated with medical irradiation or members of staff who work in the nuclear industries may receive higher radiation exposure levels than members of general public (Watson et al., 2005). The phenomenon of emission of active radiations by an element was termed radioactivity. The element exhibiting this property was called radioactivity element. the knowledge of the concentrations and distributions of the natural radionuclide in the sediments are of great interest since it provides useful information in monitoring of environmental contamination and associated human health by natural radioactivity (G. Suresh et al., 2011). Today we know that this radiation primarily consists of positively charged nuclei. Of the primary charged particles in cosmic rays, $\approx 90\%$ are protons, $\approx 9\%$ are helium nuclei and $\approx 1\%$ are electrons. This radiation spans an enormous energy range, from $\approx 10^9$ eV up to $\approx 10^{20}$ eV (S. Tavernier, 2010)

1 Radioactivity in Environment

The exposure of human beings to naturally occurring radiation arises mainly from two different origins (UNSCEAR, 2000). The first source comes directly from cosmic radiation from the outer space. The interactions of cosmic-ray particles in the atmosphere can create a number of radioactive nuclei such as ^3H , ^7Be , and ^{14}C (NCRP, 1975). The other main contributor is the terrestrial radioactive materials which originate from the formation of the

earth and are present everywhere in the earth's crust, and in the human body itself. Apart from the exposure from direct cosmic rays and cosmogenic radionuclides, natural exposures arise mainly from the primordial radionuclides which are spread widely and are present in almost all geological materials in the earth's environment (NCRP, 1975, Wilson, 1994). These radionuclides are known as Naturally Occurring Radioactive Material or by the acronym 'NORM' (World Nuclear Association, 2011, Wilson, 1994). Only very long-lived nuclides, with decay half-lives comparable to the age of the earth, and their decay products, contribute to this natural radiation background in significant quantities (UNSCEAR, 2000). The majority of naturally occurring radionuclides belong to the radionuclides in the ^{238}U and ^{232}Th series, and the single decay radionuclide, ^{40}K (IAEA, 2003). Those radionuclides which emit either alpha or beta particles may be taken into the body by ingestion or inhalation and can give rise to internal exposures. Additionally, some of these nuclear species may emit gamma rays following their radioactive decay; these represent the main sources of external (whole body) exposures to humans (Watson et al., 2005, UNSCEAR, 2000).

2 Radioactivity Sources in Environment

Humans are exposed to environmental radiation from various sources (Klement, 1982, NCRP, 1975). The origin of radioactivity in the environment can be divided into two main sources, natural and man-made sources (Lilley, 2001, Klement, 1982, NCRP, 1975). The naturally occurring radiation arises mainly from terrestrial radioactive nuclides which are widely distributed in the earth's crust and extra-terrestrial sources arising from cosmic ray bombardment (Lilley, 2001, Eisenbud, and Gesell, 1997, Klement, 1982), UNSCEAR, 2000, NCRP, 1975). Other sources arise from human activities concerned with the use of radiation and radioactive materials from which releases of radionuclides into the environment may occur (Eisenbud, and Gesell, 1997, Klement, 1982).

2.1 Natural Sources

The naturally occurring radioactive material or NORM which give rise to radiation exposure for humans surrounding are comprised of isotopes which occur individually or are components of the three main radioactive decay series (Eisenbud, and Gesell, 1997, NCRP, 1975). These radionuclides can be categorized into two types, the primordial and cosmogenic, in relation to their origin (Eisenbud, and Gesell, 1997, NCRP, 1975).

2.1.1 Primordial Radionuclides

The radionuclides which are of terrestrial origin and have been on earth since its formation of the earth are known as primordial radionuclides. These radionuclides have very long decay half-lives, comparable to the age of the earth (Lilley, 2001, Klement, 1982, Watson et al., 2005, Wilson, 1994). They are ubiquitous in the earth's crust and are consequently assumed to represent a primordial inventory. The primordial radionuclides can be further sub-classified

into the series and non-series radionuclides (Eisenbud, and Gesell, 1997, NCRP, 1975). The main primordial radionuclides are listed in (Table 1.1).

2.1.2 Cosmic Radiation

Radioactivity in term of cosmic radiation comes from both the primary energetic protons and alpha particles of extraterrestrial origin that strike the earth's atmosphere and the secondary particles or cosmogenic radionuclides which are continuously generated by bombardment of stable nuclides in the atmosphere from these cosmic rays (Watson et al., 2005, NCRP, 1975).

2.1.3 Cosmogenic Radionuclides

Most of the important cosmogenic radionuclides are produced continuously by the interaction of nucleons released from cosmic radiation with target nuclei in the earth atmosphere, mostly upper atmosphere (Eisenbud, and Gesell, 1997, NCRP, 1975, Cember, and Johnson, 2009). These interactions lead to a variety of spallation or neutron capture reactions (Klement, 1982, UNSCEAR, 2000). Spallation and charge exchange results in lighter or the same mass radionuclides being created compared with the target atom. By contrast, the products of neutron capture are radionuclides which have one mass unit heavier than the original stable 'target' nuclide. The majority of target atoms in the earth's atmosphere are from argon, oxygen, and nitrogen gases. A large number of cosmic-ray produced radioactive isotopes can be found all around the earth. There are several cosmogenic radionuclides with a range of half-lives from minutes to millions of years; however, only four of them contribute a significant measurable dose of radioactivity to humans (Eisenbud, and Gesell, 1997, NCRP, 1975). From a radiation health aspect, the main cosmogenic radionuclides are tritium (^3H), beryllium-7 (^7Be), carbon-14 (^{14}C) and sodium-22 (^{22}Na) (Eisenbud, and Gesell, 1997, Watson et al., 2005, NCRP, 1975). The most significant cosmogenic radionuclide is ^{14}C which can be taken up by plants and becomes enter the food chain (Watson et al., 2005).

2.2 Man-made (Anthropogenic) Sources

Some of the radionuclides have been released into the environment due to the use of radiation sources by man for various purposes (Klement, 1982). Detectable quantities of man-made radionuclides are widely distributed in the atmosphere, particularly as a result of nuclear weapons testing and the Chernobyl reactor accident in 1986 (Lilley, 2001, Klement, 1982, Watson et al., 2005, NCRP, 1977). A significant radionuclide produced from these sources is ^{137}Cs with half-life of 30.7 years. This nuclide has been globally dispersed and deposited through rain and dry deposition on terrestrial surfaces (Watson et al., 2005). It can be taken up by plants and subsequently be incorporated into foodstuffs (Watson et al., 2005). However, the environmental levels of released radionuclides are slowly declining and some of them are below the limits of detection. Other sources may be released from nuclear power fuel cycle (Lilley, 2001, Adloff, and Guillaumont, 1993).

3 Radioactive Decay

Radioactivity is a statistical process describing the spontaneous transformation of unstable atomic nuclei (called ‘parent nuclei’) into a more stable configuration (called ‘daughter’ nuclei) (Lilley, 2001, L’Annunziata, 2007, NCRP, 1985) without the effect of physical and

Table 1.1: Lists of primordial radionuclides (Eisenbud, and Gesell, 1997, Watson et al., 2005, UNSCEAR, 2000).

| <i>Nuclide</i> | <i>Decay Mode</i> | <i>Half-life (years)</i> | <i>Isotopic Abundance (%)</i> | <i>Stable Disintegration</i> |
|---------------------------|-------------------|--------------------------|-------------------------------|--------------------------------------|
| ⁴⁰ K | β, ε, γ | 1.3 × 10 ⁹ | 0.0117 | ⁴⁰ Ar, ⁴⁰ Ca |
| ⁵⁰ V | β, ε, γ | 1.4 × 10 ¹⁷ | 0.25 | ⁵⁰ V, ⁵⁰ Ti |
| ⁸⁷ Rb | β | 4.9 × 10 ¹⁰ | 27.83 | ⁸⁷ Sr |
| ¹¹³ Cd | β | 7.7 × 10 ¹⁵ | 12.22 | ¹¹³ In |
| ¹¹⁵ In | β | 4.4 × 10 ¹⁴ | 95.71 | ¹¹⁵ Sn |
| ¹²³ Te | ε | 6.0 × 10 ¹⁴ | 0.89 | ¹²³ Sb |
| ¹³⁸ La | β, ε, γ | 1.1 × 10 ¹¹ | 0.09 | ¹³⁸ Ba, ¹³⁸ Ce |
| ¹⁴⁴ Na | α | 2.4 × 10 ¹⁵ | 23.80 | ¹⁴⁰ Ce |
| ¹⁴⁷ Sm | α | 1.1 × 10 ¹¹ | 14.99 | ¹⁴³ Nd |
| ¹⁴⁸ Sm | α | 7.0 × 10 ¹⁵ | 11.24 | ¹⁴⁴ Nd |
| ¹⁵² Gd | α | 1.1 × 10 ¹⁴ | 0.20 | ¹⁴⁸ Sm |
| ¹⁷⁴ Hf | α | 2.0 × 10 ¹⁵ | 0.16 | ¹⁷⁰ Y |
| ¹⁷⁶ Lu | β, γ | 2.8 × 10 ¹⁰ | 2.59 | ¹⁷⁶ Hf |
| ¹⁸⁶ Os | α | 2.0 × 10 ¹⁵ | 1.59 | ¹⁸² W |
| ¹⁸⁷ Re | β | 4.1 × 10 ¹⁰ | 62.60 | ¹⁸⁷ Os |
| ¹⁹⁰ Pt | α | 6.5 × 10 ¹¹ | 0.014 | ¹⁸⁶ Os |
| ²³⁸ U(Series) | α | 4.5 × 10 ⁹ | 99.27 | ²⁰⁶ Pb |
| ²³⁵ U(Series) | α | 7.0 × 10 ⁸ | 0.72 | ²⁰⁷ Pb |
| ²³² Th(Series) | α | 1.4 × 10 ¹⁰ | 100 | ²⁰⁸ Pb |

chemical condition (Choppin, et al., 2002). In case where the daughter product is also unstable, the decay process carries on until a daughter nucleus reaching stability (Lilley, 2001). Consequently, the energy of the transformation can be released by the emission of nuclear particles and/or in terms of electromagnetic radiations (L’Annunziata, 2007, Gilmore, 2008). The strength or intensity of the radioactivity is called the activity and is defined as the rate of nuclei number decaying (L’Annunziata, 2007, Kaplan, 1962, Faires, and Boswell, 1981). The probability per unit of time for the decay of a given nucleus is a constant, which can be commonly named as the disintegration or decay constant (λ) (Lilley, 2001, Krane, 1988). The

rate of radioactive decay, which is related to the activity, can be expressed by the fundamental law of radioactive decay by (Burcham, 1973, Turner, 2007).

$$A = -\frac{dN}{dt} = \lambda N \quad (1)$$

As shown in equation 1, A is the activity of an isotopically pure source, which is equal to the number, dN, of radioactive nuclei disintegrating in a given time, dt, and is proportional to the number, N, of radioactive nuclei present at time, t (L'Annunziata, 2007, Kaplan, 1962). λ is the decay constant and the negative sign indicates that the number of radioactive nuclei decrease when the time increases (Lilley, 2001, Krane, 1988, Lapp, and Andrews, 1972). Originally, the unit of activity is curie (Ci) which is based on the activity of 1 gram of Radium (^{226}Ra), which is equivalent to 3.7×10^{10} disintegrations per second (Lapp, and Andrews, 1972, Curie, et al., 1931). Currently, the becquerel (Bq) has become the standard unit of activity and is defined as one disintegration per second (Lilley, 2001, Faires, and Boswell, 1981), Knoll, 2000). Thus, 1 Ci is equal to 3.7×10^{10} Bq (L'Annunziata, 2007, Krane, 1988, Cember, and Johnson, 2009). The solution to equation 2.1 leads to the exponential law of radioactive decay, which may be written as (Faires, and Boswell, 1981, Harvey, 1969)

$$N = N_0 e^{-\lambda t} \quad (2)$$

where N is the original number of nuclei present at time $t = 0$. The number of nuclei decreases exponentially with time (Harvey, 1969). Figure 1.1 illustrates the number of nuclei decaying as a function of time. Usually, the rate of radioactive decay can be characterised in terms of a specific time frame known as the half-life (L'Annunziata, 2007, Faires, and Boswell, 1981). The half-life is the time required for one-half of a certain number of active nuclei to disintegrate (Harvey, 1969) as shown in figure 1.1.

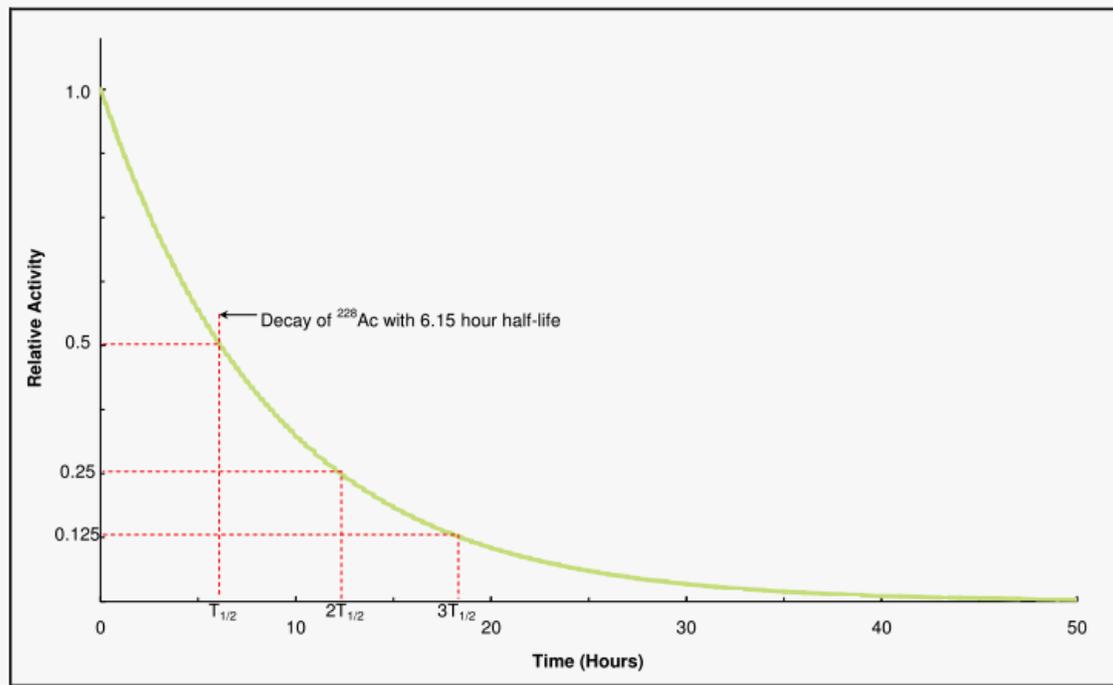


Fig 1.1: The exponential radioactive decay curve of ^{228}Ac with half-life, $T_{1/2}$.

4 Radioactive Equilibrium

Radioactive equilibrium is the term usually used to explain the state when the members of the radioactive series decay at the same rate as they are produced (Prince, 1979). The three predominant cases of the state of equilibrium can be explained as below.

4.1 Secular Equilibrium

Secular equilibrium is a steady-state condition that in which the half-life of the parent is very much greater than that of the daughter, therefore, $\lambda_p \ll \lambda_D$ (Faires, and Boswell, 1981, Burcham, 1973, Cember, and Johnson, 2009). Since, $\lambda_p \ll \lambda_D$ and $\lambda_p \approx 0$ then, $e^{-\lambda_p t} \approx 1$ and the number of the daughter nuclei can be simplified to (L'Annunziata, 2007, Krane, 1988, Lapp, and Andrews, 1972)

$$N_D(t) = N_p(0) \frac{\lambda_p}{\lambda_D} (1 - e^{-\lambda_D t}) \quad (3)$$

Consider equation 3, when time increases, the term $e^{-\lambda_D t}$ can be neglected during the growth of the daughter and the number of the daughter nuclei will reach an equilibrium value after about seven half-life of the daughter (Turner, 2007, Cember, and Johnson, 2009), Halliday, 1955). At equilibrium, the parent and daughter activities are equal, i.e., (Turner, 2007, Cember, and Johnson, 2009).

$$\lambda_p N_p = \lambda_D N_D \quad (4)$$

When secular equilibrium is established, the activity of the daughter becomes equal to that of its parent with time (L'Annunziata, 2007, Turner, 2007, Cember, and Johnson, 2009). In a decay chain, the numbers of nuclei of the various daughters present at equilibrium are inversely proportional to their decay constants and the formation rate and the decay rate of every radioactive daughter equals the decay rate of its parent, $\lambda_p N_p$ (Burcham, 1973, Cember, and Johnson, 2009, Harvey, 1969). For instance, the sequence of ^{226}Ra with half-life 1600 years to ^{222}Rn with half-life 3.8235 days is of the interest for the state of secular equilibrium. Figure 1.2, shows the build-up and establishment of secular equilibrium of ^{222}Rn from the extremely long-lived parent ^{226}Ra .

4.2 Transient Equilibrium

A different state of equilibrium, called 'transient equilibrium' can occur in which the parent half-life is longer-lived than that of the daughter but not significantly longer (L'Annunziata, 2007, Choppin, et al., 2002, Cember, and Johnson 2009), i.e., where $\lambda_p < \lambda_D$. In these cases, the approximation $\lambda_p = 0$ can not be made (Kaplan, 1962)). The exponential term of the daughter, $e^{-\lambda_D t}$ becomes much smaller and can be negligible compared with $e^{-\lambda_p t}$ after a sufficiently long period of time (L'Annunziata, 2007, Turner, 2007, Cember, and Johnson 2009). Under this condition, the number of the daughter nuclei may be written as (L'Annunziata, 2007, Kaplan, 1962, Lapp, and Andrews, 1972).

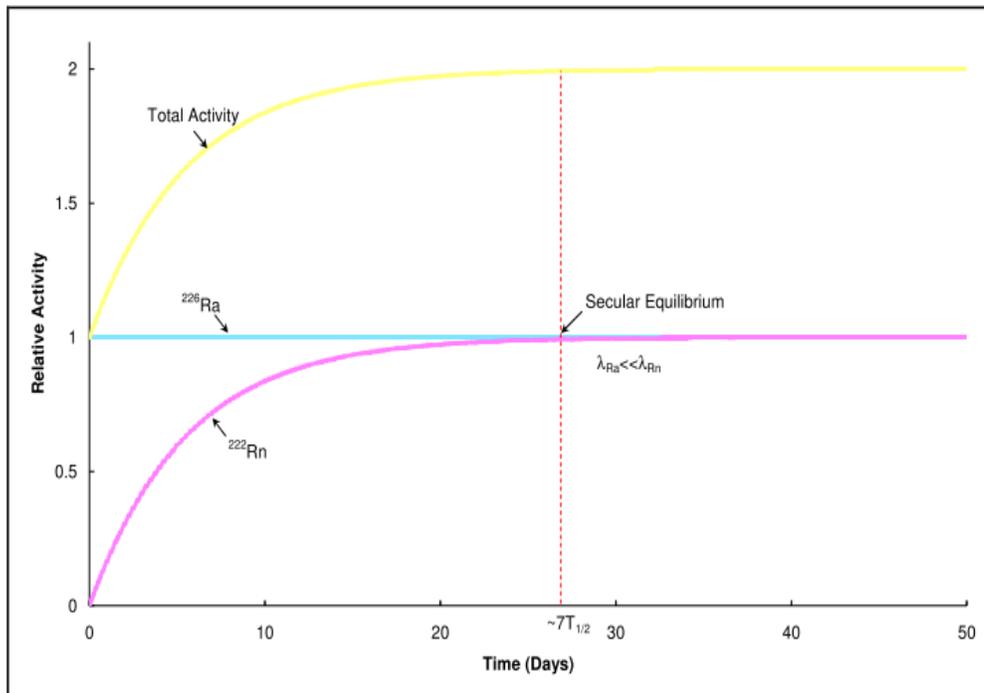


Fig 1.2: Growth of a short-lived daughter (^{222}Rn) from a much longer lived parent (^{226}Ra) until reaching Secular Equilibrium.

$$N_D(t) = N_p(0) \frac{\lambda_p}{\lambda_D - \lambda_p} (1 - e^{-\lambda_p t}) \quad (5)$$

Using equation 2 as $N_p(t) = N_p(0) e^{-\lambda_p t}$ equation 5 can be rewritten as:

$$\frac{N_D}{N_p} = \frac{\lambda_p}{\lambda_D - \lambda_p} \quad (6)$$

From equation 6, after a state of transient equilibrium exists, the ratio of the number of nuclei tends to the constant value (L'Annunziata, 2007, Kaplan, 1962, Lapp, and Andrews, 1972) and the parent and daughter nuclides will decay at the same rate, related to the decay of parent which is the characteristic of transient equilibrium (Lapp, and Andrews, 1972, Cember, and Johnson 2009, Harvey, 1969). An example of transient equilibrium is the decay of ^{212}Pb with half-life 10.64 hours to ^{212}Bi with half-life 60.55 minutes shown in Figure 1.3. The time at which equilibrium between the parent and daughter nuclides will be established depends on the magnitudes of their half-lives (Lapp, and Andrews, 1972, Cember, and Johnson 2009]. The shorter the half-life of the daughter compared with the parent, the faster the state of equilibrium will be reached (Cember, and Johnson 2009).

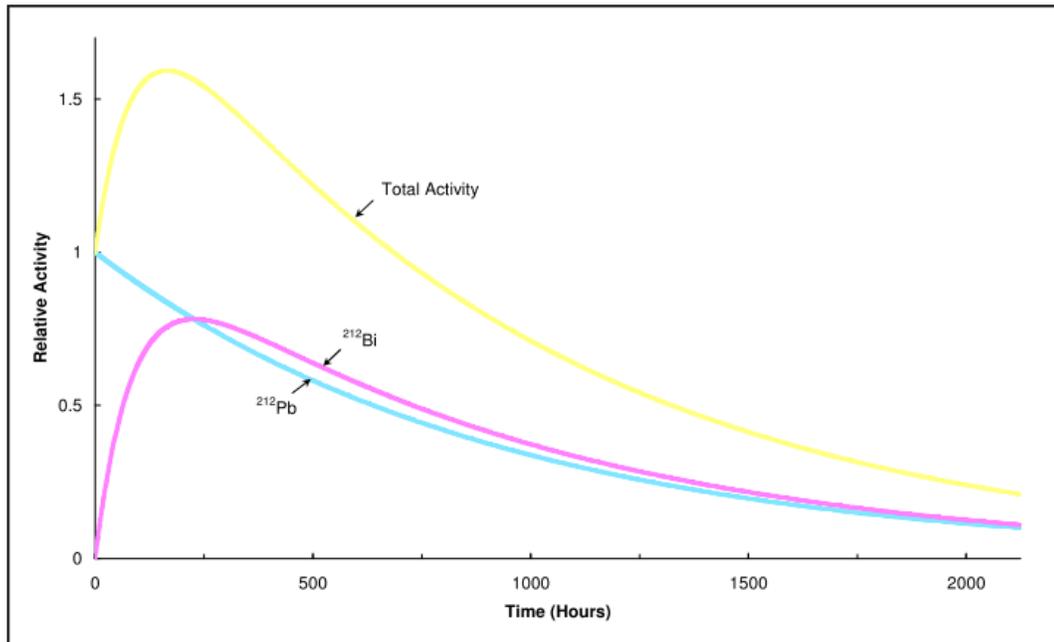


Fig 1.3: Growth and decay of a short-lived daughter (^{212}Bi) from a slightly longer-lived parent (^{212}Pb) in Transient equilibrium.

4.3 No Equilibrium

In case the half-life of the parent nuclide has shorter lived than that of the daughter product, the state of equilibrium will not be attained (Krane, 1988, Turner, 2007, Cember, and Johnson 2009). For long times, the term $e^{-\lambda_p t}$ can be negligible and the calculation of the daughter decay can be given by (Krane, 1988, Lapp, and Andrews, 1972)

$$N_D(t) = N_p(0) \frac{\lambda_p}{\lambda_D - \lambda_p} (1 - e^{-\lambda_D t}) \quad (6)$$

The parent, owing to its shorter half-life, will decay away while the number of daughter nuclei build up to a maximum and then decrease eventually with its own characteristic half-life (Choppin, et al., 2002, Turner, 2007, Cember, and Johnson 2009). Figure 1.4 illustrates the decay of ^{218}Po with half-life 3.1 minutes to ^{214}Pb with half-life 26.8 minutes without the state of equilibrium. Note that the activity only describes the number of disintegrations per second and says nothing about the kind of radiations emitted or their energies (Krane, 1988). The next section will describe types of radiations and their characteristic.

5 Interaction of Gamma Rays with Matter

Due to the properties of gamma radiation, the interaction of gamma rays with matter is different in that they have much greater penetration power and longer ranges than the charged, massive alpha and less-massive beta particles. The significant characteristic of gamma radiation absorption in matter is an exponential decay function with depth, without a well-defined range, as is observed for charged particles (Lilley, 2001, Knoll, 2000, Cember, and Johnson 2009). An uncharged gamma-ray photon can interact with electrons in the absorbing material and transfer all or part of its energy to electrons leading to indirect ionization. Interaction of gamma-ray photons with matter can occur by various mechanisms, but only three mechanisms play the most significant roles in radiation measurement (Knoll, 2000, Turner, 2007, Debertin, K. and Helmer, 1988). The processes of photoelectric absorption, Compton scattering, and pair production all contribute to the observed response in gamma ray spectrometry (Knoll, 2000). Some fundamentals of the gamma ray interaction processes are introduced in the following subsection.

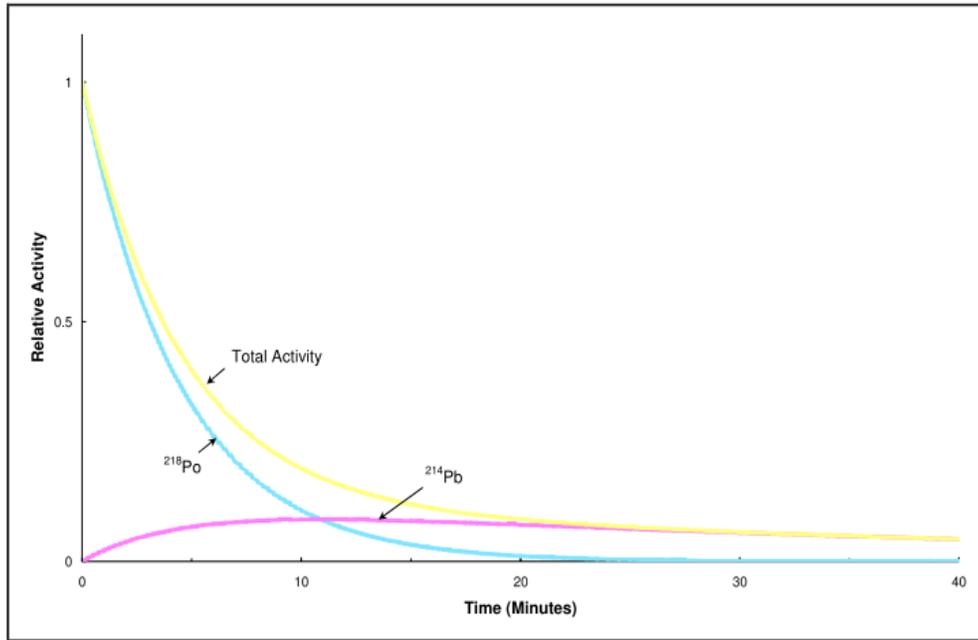


Fig 1.4: Growth and decay of a longer-lived daughter (^{218}Po) from a short-lived parent (^{214}Pb) in case of no equilibrium.

5.1 Photoelectric Absorption

In the process of photoelectric absorption, a photon interacts with a bound electron in an absorber material in which the photon is completely absorbed. Then, an energetic electron called photoelectron is ejected from one of the electron shells with a kinetic energy given by the incident photon energy (νh) minus the binding energy of the electron in its origin shell (E_b). For typical gamma-ray energies, the emission of the photoelectron is likely to originate from the most tightly bound or, K-shell, of the atom. The binding energies of these K-shell electrons vary from a few keV for low-Z materials to tens of keV for material with higher atomic number (Knoll, 2000). The photoelectric absorption process is shown schematically in the diagram below.

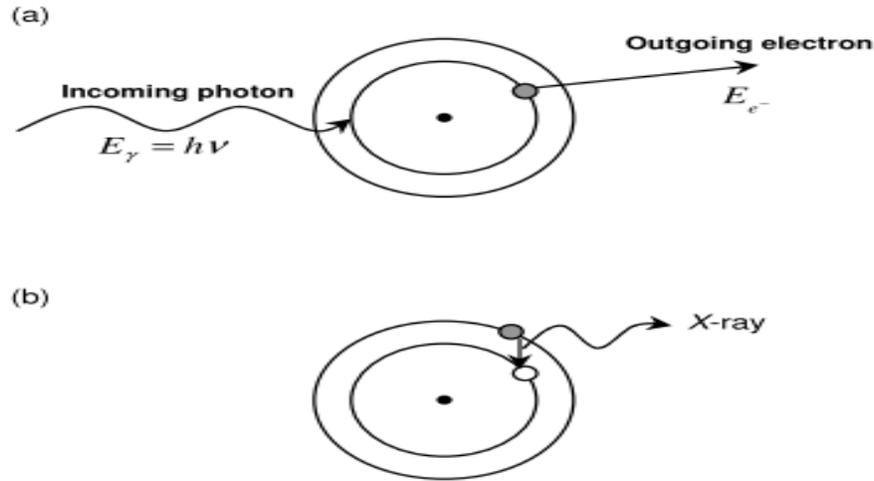


Fig 1.5: Schematic of the photoelectric absorption process.

As can be seen in Figure 1.5 (a), the outgoing electron is ejected with a kinetic energy given by (Lapp, and Andrews, 1972, Cember, and Johnson 2009, Das, and Ferbel, 2003).

$$E_{e^-} = h\nu - E_b \quad (7)$$

The photoelectron emission also creates a vacancy in a shell of the atom resulting in an excited state. The de-excitation of the atom can occur by the electron arrangement from higher shells to fill in a vacancy leading to the emission of characteristic X-ray shown in Figure 5 (b). Alternatively, the excitation energy can be carried away by the release of other, less tightly bound electrons known as Auger electrons. The interaction cross section (τ) of the photoelectric process varies in a complex manner with E_γ and with the value of Z of the absorber. A single analytic expression cannot describe the probability of this process, but an approximation can be given by (Lilley, 2001, Eisenbud, and Gesell, 1997, Knoll, 2000):

$$\tau \cong \text{constant} \frac{Z^n}{E_\gamma^m} \quad (8)$$

where the power indices n and m are numbers ranging from 3 to 5 over the gamma-ray energy region of interest. The photoelectric absorption probability strongly depends on photon energy and atomic number of an absorber material. The strong Z dependence indicates that a high- Z material is very effective in the absorption of photons. The strong dependence on the photon energy is the reason why the photoelectric process is significant at low energy of photons but becomes less dominant at higher energies.

5.2 Compton Scattering

The Compton scattering process describes a collision between the incident gamma-ray photon and weakly bound or free electron in the absorbing material. Instead of giving up its entire energy, only a portion of the photon energy is transferred to the electron. The result of this

interaction is that the incoming gamma-ray photon is degraded in energy and deflected from its original direction and an electron known as a recoil electron is created. From the laws of conservation of total mass-energy and linear momentum, the energies of the scattered photon and recoil electron are related to the angles at which they are emitted. Figure 1.6 shows a schematic of the Compton scattering process.

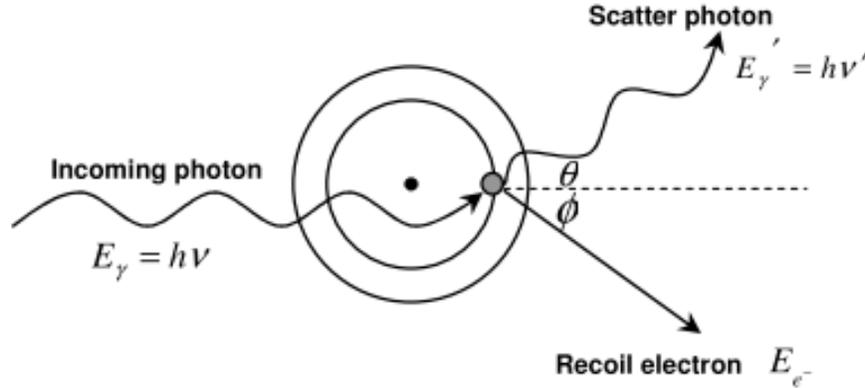


Fig 1.6: Schematic of the Compton scattering process.

The energy of the scattered gamma-ray $h\nu'$ is related to its scattering angle θ by the expression (L'Annunziata, 2007, Kaplan, 1962, Das, and Ferbel, 2003):

$$h\nu' = \frac{h\nu}{1 + \left(\frac{h\nu}{m_0c^2}\right)(1 - \cos\theta)} \quad (9)$$

where $m_0c^2 = 511$ keV represents the rest mass energy of the electron. It then follows that the kinetic energy of the recoil electron is given by (Gilmore, 2008, Lapp, and Andrews, 1972):

$$E_{e^-} = h\nu - h\nu' = h\nu \left(\frac{\left(\frac{h\nu}{m_0c^2}\right)(1 - \cos\theta)}{1 + \left(\frac{h\nu}{m_0c^2}\right)(1 - \cos\theta)} \right) \quad (10)$$

The energy of the recoil electron can vary from zero ($\theta = 0$) up to a maximum value ($\theta = \pi$) depending upon the angle of scatter. The maximum energy of the recoil electron is given by:

$$E_{e^-} = \frac{2h\nu}{2 + \frac{m_0c^2}{h\nu}} \quad (11)$$

The probability of Compton scattering depends strongly on the number of electrons per unit mass of the interacting material. It also depends on the incoming gamma-ray energy as function of $1/E_\gamma$ (Lilley, 2001, Gilmore, 2008). Compton scattering is the dominant interaction process for gamma-ray energies ranging from 0.1 to 10 MeV (Das, and Ferbel, 2003). At higher energy, another interaction mechanism, known as 'pair production' becomes more significant.

5.3 Pair Production

The third significant interaction mechanism of gamma-rays with matter is pair production. This process becomes increasingly important when the incident gamma-ray photon has energy significantly greater than twice the rest mass energy of an electron ($2m_0c^2 = 1.022$ MeV). This interaction occurs within the Coulomb field of a nucleus in which the gamma-ray photon is absorbed into the vacuum and is converted into an electron-positron pair. Since an initial photon energy of at least $2m_0c^2$ is required for the creation of the electron-positron pair, any excess energy ($E_\gamma - 2m_0c^2$) carried in by the photon above 1.022 MeV is imparted to and shared equally by the positron and the electron as kinetic energy, given by (Knoll, 2000, Lapp, and Andrews, 1972):

$$E_{e^-} + E_{e^+} = h\nu - 2m_0c^2 \quad (12)$$

After electron and positron pair is created, they can traverse the medium, losing their kinetic energy by collisions with electrons in the surrounding material through ionization, excitation and/or bremsstrahlung. Once, the positron slows down, it can combine with an atomic electron in the surrounding material and subsequently annihilate to form two photons, called annihilation photons, each with energies of about $m_0c^2 = 0.511$ MeV. In order to conserve linear momentum these two photons must be emitted in opposite direction, i.e., back to back. Figure 1.7 depicts the schematic diagram of the pair production process.

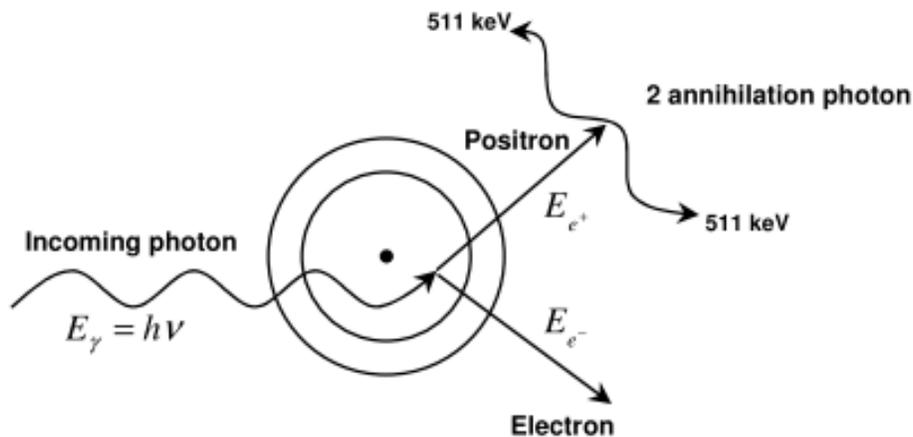


Fig 1.7: Schematic of the pair production process and annihilation.

6 Radiation Detection

There are various types of radiation detectors such as gas, scintillation or semiconductor detectors (Lilley, 2001, Knoll, 2000, Cember, and Johnson 2009). Some of them may provide different types of information about radiation, such as its energy, intensity, and/or the type of radiation which is being measured. The difference of each detector depends on its detecting

medium which can be gas, liquid or solid materials. All types of radiation detection instruments however basically involve generating electrical signals which result from the interaction of radiation with the detector material. The detection methods are, in general, based on the process of excitation or ionization of atoms in the detector by the passage of a charged particle. Electromagnetic radiation gives rise to energetic electrons by one of the three types of processes, namely photoelectric effect, Compton scattering and pair production as outlined in section 1.6.

Gas-filled detectors are really suitable only for counting low energy electrons, ions and photons due to the poor stopping capability of gas as detection medium for gamma rays. In order to improve the absorption probability of a detecting medium, higher atomic number and/or higher density liquid or solid materials are used to measure highly penetrating radiations (Gilmore, 2008, Krane, 1988). Detectors which are based on the process of scintillation can be used for detecting ionizing radiation and this is one of the oldest and most useful techniques for the detection and spectroscopy of a wide range of radiations (Lilley, 2001, Knoll, 2000). For gamma-ray spectrometry, thallium-activated sodium iodide scintillator (NaI (Tl)) is the most frequently used because it has a high efficiency for detecting gamma radiation and does not require cooling. However, scintillation detectors do not provide the energy selectivity to deal with a complex gamma-ray spectrum, due to their relatively poor energy resolution (Knoll, 2000, Cember, and Johnson 2009). To achieve a good energy resolution, semiconductor detectors are used. The experimental work presented in this thesis project used germanium semiconductor detectors, as described in the following section.

6.1 Counting System for Gamma-ray Spectrometry

The interactions of incident gamma radiations with a detector undergoing any of the three principal interaction processes generates a number of electronic secondary charges which are proportional to the amount of gamma-ray energy deposited in the detector. The electrical charge output from the detector will be collected and counted through an electronic counting system as illustrated in Figure 1.8 and then displayed in form of the gamma-ray spectrum.

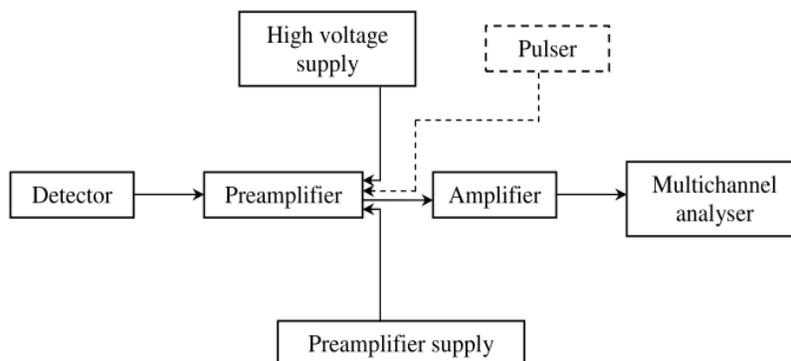


Fig 1.8: A simple schematic electronic system for gamma-ray spectrometry (Gilmore, 2008).

A detector bias supply is connected to a detector in order to withdraw the electron-hole pairs created within the depletion region of a detector and then all charge carriers will be collected by the preamplifier. The preamplifier converts the collected charge pulse to a voltage pulse. The shape and size of the preamp pulse are modified to be suitably processed by the amplifier. Due to the amplifier being linear, the pulse height is proportional to the gamma-ray energy, which was absorbed. The pulses from the amplifier are sorted by their pulse height and then converted to a digital number referred as a channel by the analog-to-digital converter (ADC) in the multichannel analyzer (MCA). The number of pulses according to each pulse height range is counted and stored in each channel number that contributes to a gamma-ray spectrum.

7 Biological Effects of Radiation

When the human body is exposed to any radiation, either from external or internal sources, ionization and excitation of atoms and molecules can be produced. Consequently, the interaction of radiation with biological organisms can result in the damage and death of living cells and/or the mutation of genetic material. The variation of the biological effects of radiation depends on types of radiation and its energy which is transferred to the irradiated parts of tissues and organs during the exposure time (Lilley, 2001, Eisenbud, and Gesell, 1997, Noz, and Maguire 2007). The quantification of the amount of ionization which occurred and the energy absorbed by particular cells associated with biological effectiveness can be considered in terms of radiation dosimetry.

7.1 Exposure

The 'roentgen' (R) is the unit to express the radiation exposure that can be defined as the amount of ionization that X- or γ radiation produces in air. This unit accounts for the production of 1 esu of electrical charge of either sign in 1 cm³ or 0.001293 g of air at standard temperature and pressure (Turner, 2007, Harvey, 1969). Since 1 esu = 3.34 x 10⁻¹⁰ coulomb (C) (Turner, 2007).

7.2 Absorbed Dose

One limitation of the exposure unit is that it does not reflect the biological significance of the radiation. A unit considering the quantity of energy absorption by any kind of ionizing radiation in any kind of material was introduced. The absorbed dose is measured in units of 'gray' (Gy) where 1 Gy equals to one joule of absorbed energy per one kilogram of irradiated target (Lilley, 2001, Cember, and Johnson 2009, Noz, and Maguire 2007). The absorbed dose can be expressed in another unit called the 'rad' (radiation absorbed dose). The rad is the original unit and is defined as an absorbed energy of 100 erg per gram.

The total absorbed energy is not the only factor which determines the level of biological damage from the radiation. The type of radiation and its energy also have to be considered. In general, the biological effect of highly ionizing radiation in a tissue is more severe per unit

absorbed dose than those of radiation which produce low ionization. For this reason, the term relative biological effectiveness (RBE) was introduced as a dimensionless quantity of the amount of absorbed dose of ionizing radiation relative to that of X- or γ radiation of a particular energy to provide the same biological response (Lilley, 2001, Cember, and Johnson 2009, Noz, and Maguire 2007). Due to the difficulty in applying such complicated functions of energy, RBE has been normalized to a factor known, as the radiation weighting factor (w_R) by the ICRP and NCRP (Cember, and Johnson 2009, Noz, and Maguire 2007). This factor is derived from the RBE over the range of energies for a particular type of radiation. A list of radiation weighting factors for various types of ionizing radiation is presented in (Table 1.2).

7.3 Equivalent and Effective Dose

In order to determine the effect of the nature of the radiation by the weighting factor in (Table 1.2), a unit called the equivalent dose (H_T) is specified. This is the amount of the dose ($D_{T,R}$) absorbed over a tissue or organ (T) due to radiation (R) and is given by (Lilley, 2001, Eisenbud, and Gesell, 1997. Cember, and Johnson 2009, Noz, and Maguire 2007):

$$H_T = \sum_R w_R D_{T,R} \quad (13)$$

Table 1.2: Radiation weighting factors for different ionizing radiations (Cember, and Johnson 2009, Noz, and Maguire 2007, ICRP, 1991)

| Type of Radiation | Energy range | Weighting factor, w_R |
|---|-------------------|-------------------------|
| Photon, electrons, positrons and muons | All energies | 1 |
| Neutrons | <10 keV | 5 |
| | >10 keV to 2 MeV | 10 |
| | >100 keV to 2 MeV | 20 |
| | >2 MeV to 20 MeV | 10 |
| | >20 MeV | 5 |
| Protons | <20 MeV | 5 |
| Alpha particles, fission fragments, non-relativistic heavy nuclei | | 20 |

The 'sievert' (Sv) is used to express the equivalent dose when the absorbed dose is in units of gray (Gy); thus one sievert is also equal to one joule per kilogram. An older unit of the equivalent dose is the 'rem' (radiation equivalent man) with the absorbed dose expressed in units of rad (Choppin, et al., 2002), hence, 1 Sv equals to 100 rem (Lilley, 2001, Eisenbud, and Gesell, 1997, Choppin, et al., 2002, Knoll, 2000, Turner, 2007). In addition to the radiation types and energy, the biological effect to radiation is concerned with the sensitivities of irradiated organs or tissues. The variation of radiation sensitivity of each organ is taken into

account in the contribution of the equivalent dose in all tissues and organs of the body. The new terms the effective dose (E) and the tissue weighting factor (w_T) are introduced. The definition of the effective dose is the sum of the equivalent doses weighted by the tissue weighting factors for each tissue, as given in the following expression (Cember, and Johnson 2009, Noz, and Maguire 2007)

$$E = \sum_T w_T H_T \quad (14)$$

Considering equations 13 and 14,

$$E = \sum_T w_T \sum_R w_{R,T} \quad (15)$$

Table 1.3 lists the tissue weighting factors for tissues and organs of the human body. These factors were obtained from a reference population of equal numbers of men and women ranging in age. Because of the normalization of all tissue weighting factor values is unity; the effective dose equals a uniform equivalent dose over the whole body (Noz, and Maguire 2007, ICRP, 1991). The SI unit of effective dose is also the sievert (Sv).

Table 1.3: Tissue weighting factors (Noz, and Maguire 2007, ICRP, 1991).

| Tissue or Organ | Tissue weighting factors, w_T |
|-----------------|---------------------------------|
| Gonads | 0.20 |
| Colon | 0.12 |
| Lung | 0.12 |
| Red bone marrow | 0.12 |
| Stomach | 0.12 |
| Bladder | 0.05 |
| Breast | 0.05 |
| Oesophagus | 0.05 |
| Liver | 0.05 |
| Thyroid | 0.05 |
| Skin | 0.01 |
| Bone surfaces | 0.01 |
| Remainder | 0.05 |

In this chapter we take a view and brief introduction of discovery of radioactive and also we talk about naturally occurring radiation so it is so important to introduce the source of radioactivity and its different types in the environments. We talk about Natural sources (Primordial radionuclides, Cosmic radiation and Cosmogenic radionuclides) and man-made (Anthropogenic) Sources and discuss every one individually, we not forget to talk about Radioactive decay theory and its equilibrium also we write introduction of interaction gamma

rays with matters and its types (Photoelectric Absorption Compton Scattering and Pair Production), we discuss the radiation detection and it's important to talk about Counting System for Gamma-ray Spectrometry which we use in our work, and for human health we introduce biological effects of radiation, so in chapter 2 deals with Red Sea Morphology, Geological Setting, meteorology and oceanographic parameters. It summarizes the description of the physical parameters and behavior of air, sea and land of the Red Sea environment. Also deal with description of the studied areas, we do a thorough explanation for the study area also included a sufficient description for the station that we collected the samples from it.

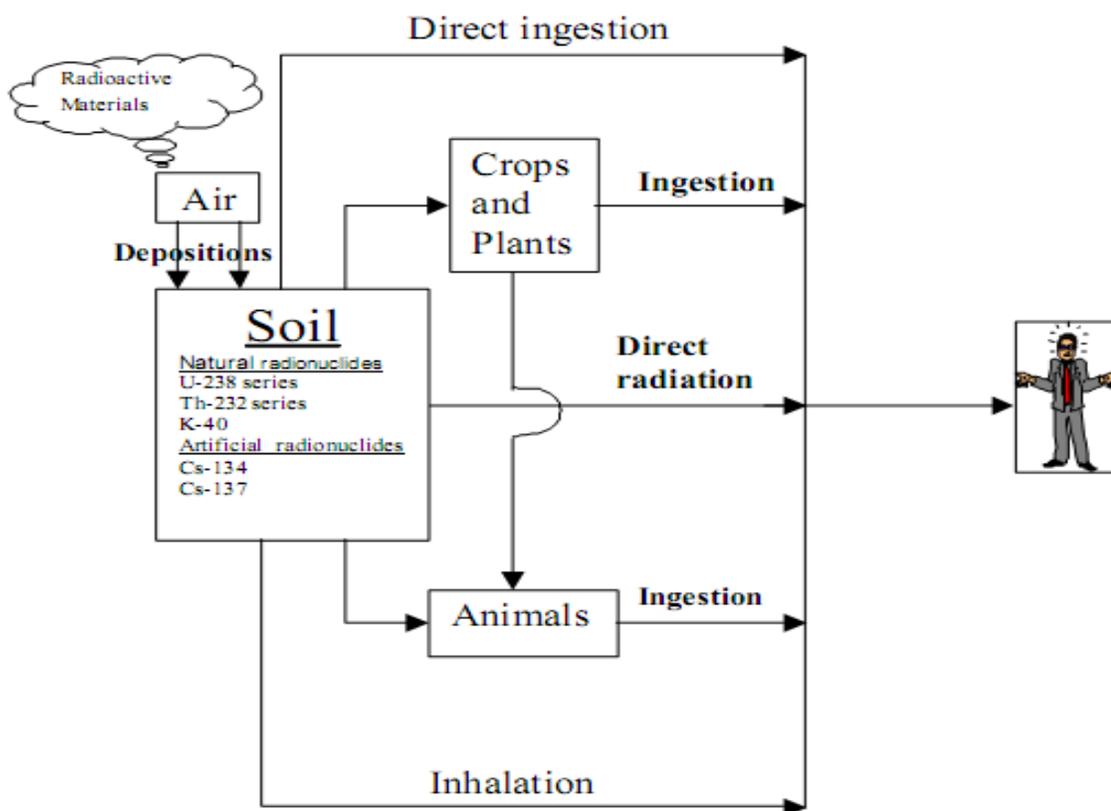


Fig. 1.9: shows some of the possible pathways of contamination to humans.

Source: "Considerations for Environmental Gamma Spectroscopy Systems" available at <http://www.canberra.com/literature/972.asp>(2002).