Basic Sciences of Nuclear Medicine

Magdy M. Khalil (Ed.)

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Magdy M. Khalil
Imperial College London
Hammersmith Campus
Biological Imaging Centre
Du Cane Road
W12 0NN London
United Kingdom
magdy_khalil@hotmail.com

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*I dedicate this book to my parents*

وفوق كل ذي علم عليم.....سورة يوسف (76)

"... and over every lord of knowledge, there is ONE more knowing"
Yousef (12:76)

# Acknowledgment

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# Part I

# Physics and Chemistry of Nuclear Medicine

# Basic Physics and Radiation Safety in Nuclear Medicine

1

G. S. Pant

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## 1.1 Basic Atomic and Nuclear Physics

### 1.1.1 Atom

All matter is comprised of atoms. An atom is the smallest unit of a chemical element possessing the properties of that element. Atoms rarely exist alone; often, they combine with other atoms to form a molecule, the smallest component of a chemical compound.

G.S. Pant
Consultant Medical Physicist, Nuclear Medicine Section, KFSH, Dammam, KSA
e-mail: gspant2008@hotmail.com

### 1.1.2 Modern Atomic Theory

#### 1.1.2.1 Wave-Particle Duality

According to classical physics the particle cannot be a wave, and the wave cannot be a particle. However, Einstein, while explaining the photoelectric effect (PEE), postulated that electromagnetic radiation has a dual wave-particle nature. He used the term *photon* to refer to the particle of electromagnetic radiation. He proposed a simple equation to relate the energy of the photon $E$ to the frequency $v$ and wavelength $\lambda$ of electromagnetic wave.

$$E = hv = h\frac{c}{\lambda} \tag{1.1}$$

In this equation, $h$ is Planck's constant ($6.634 \times 10^{-34}$ J.s) and $c$ is the velocity of light in a vacuum.

De Broglie generalized the idea and postulated that all subatomic particles have a wave-particle nature. In some phenomena, the particle behaves as a particle, and in some phenomena it behaves as a wave; it never behaves as both at the same time. This is called the *wave-particle duality of nature*. He suggested the following equation to relate the momentum of the particle $p$ and wavelength $\lambda$:

$$\lambda = \frac{h}{p} \tag{1.2}$$

Only when the particles have extremely small mass (subatomic particles) is the associated wave appreciable. An electron microscope demonstrates the wave-particle duality. In the macroscopic scale, the De Broglie theory is not applicable.

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#### 1.1.2.2 Electron Configuration

Electrons around a nucleus can be described with wave functions [1]. Wave functions determine the location, energy, and momentum of the particle. The square of a wave function gives the probability distribution of the particle. At a given time, an electron can be anywhere around the nucleus and have different probabilities at different locations. The space around the nucleus in which the probability is highest is called an *orbital*. In quantum mechanics, the orbital is a mathematical concept that suggests the average location of an electron around the nucleus. If the energy of the electron changes, this average also changes. For the single electron of a hydrogen atom, an infinite number of wave functions, and therefore an infinite number of orbitals, may exist.

An orbital can be completely described using the corresponding wave function, but the process is tedious and difficult. In simple terms, an orbital can be described by four quantum numbers.

- The principal quantum number $n$ characterizes the energy and shell size in an atom. It is an integer and can have a value from 1 to $\infty$, but practically $n$ is always less than 8. The maximum number of electrons in orbital $n$ is $2n^2$. The shells of electrons are labeled alphabetically as $K(n = 1)$, $L(n = 2)$, $M(n = 3)$, and so on based on the principal quantum number.
- The orbital quantum number $l$ relates to the angular momentum of the electron; $l$ can take integer values from 0 to $n - 1$. In a stable atom, its value does not go beyond 3. The orbital quantum number characterizes the configuration of the electron orbital. In the hydrogen atom, the value of $l$ does not appreciably affect the total energy, but in atoms with more than one electron, the energy depends on both $n$ and $l$. The subshells or orbitals of electrons are labeled as s($l$ =0), p(l = 1), d(l = 2)and f(l = 3).
- The azimuthal or magnetic quantum number $m_l$ relates to the direction of the angular momentum of the electron and takes on integer values from $-l$ to $+l$.
- The spin quantum number $m_s$ relates to the electron angular momentum and can have only two values: −½ or +½.

Pauli in 1925 added a complementary rule for arrangement of electrons around the nucleus. The postulation is now called *Pauli's exclusion principle* and states that no two electrons can have all quantum numbers the same or exist in identical quantum states.

The filling of electrons in orbitals obeys the so-called Aufbau principle. The Aufbau principle assumes that electrons are added to an atom starting with the lowest-energy orbital until all of the electrons are placed in an appropriate orbital. The sequence of energy states and electron filling in orbitals of a multi-electron atom can be represented as follows:

$$1s - 2s - 2p - 3s - 3p - 4s - 3d - 4p - 5s - 4d - 5p - 6s - 4f - 5d - 6p - 7s - 5f - 6d - 7p$$

#### 1.1.2.3 Electron Binding Energies

The bound electrons need some external energy to make them free from the nucleus. It can be assumed that electrons around a nucleus have negative potential energy. The absolute value of the potential energy is called the *binding energy*, the minimum energy required to knock out an electron from the atom.

#### 1.1.2.4 Atomic Emissions

For stability, electrons are required to be in the minimum possible energy level or in the innermost orbitals. However, there is no restriction for an electron to transfer into outer orbitals if it gains sufficient energy. If an electron absorbs external energy that is more than or equal to its binding energy, a pair of ions, the electron and the atom with a positive charge, is created. This process is termed *ionization*. If the external energy is more than the binding energy of the electron, the excess energy is divided between the two in such a way that conservation of momentum is preserved.

If an electron absorbs energy and is elevated to the outer orbitals, the original orbital does not remain vacant. Soon, the vacancy will be filled by electrons from the outer layers. This is a random process, and the occupier may be any electron from the outer orbitals. However, the closer electron has a greater chance

to occupy the vacancy. In each individual process of filling, a quantum of energy equal to the difference between the binding energies $E_2 - E_1$ of the two involved orbitals is released, usually in the form of a single photon. The frequency $v$ and wavelength $\lambda$ of the emitted photon (radiation) are given as follows:

$$E_2 - E_1 = \Delta E = hv = h\frac{c}{\lambda} \tag{1.3}$$

When an atom has excess energy, it is in an unstable or *excited state*. The excess energy is usually released in the form of electromagnetic radiation (characteristic radiation), and the atom acquires its natural *stable state*. The frequency spectrum of the radiation emitted from an excited atom can be used as the fingerprint of the atom.

#### 1.1.2.5 Nuclear Structure

There are several notations to summarize the nuclear composition of an atom. The most common is ${}^{A}_{Z}X_{N}$, where X represents the chemical symbol of the element. The chemical symbol and atomic number carry the same information, and the neutron number can be calculated by the difference of A and Z. Hence, for the sake of simplicity the brief notation is ${}^{A}X$, which is more comprehensible. For example, for ${}^{137}Cs$, where 137 is the mass number (A + Z), the Cs represents the 55th element (Z = 55) in the periodic table. The neutron number can easily be calculated (A − Z = 82). Table 1.1 shows the mass, charge, and energy of the proton, neutron, and electron.

#### 1.1.2.6 Nuclear Forces

Protons in a nucleus are close to each other ($\approx 10^{-15}m$). This closeness results in an enormously strong repulsive force between protons. They still remain within the nucleus due to a strong attractive force between nucleons that dominates the repulsive force and makes the atom stable. The force is effective in a short range, and neutrons have an essential role in creating such a force. Without neutrons, protons cannot stay close to each other.

In 1935, Yukawa proposed that the short-range *strong force* is due to exchange of particles that he called *mesons*. The strong nuclear force is one of the four fundamental forces in nature created between nucleons by the exchange of mesons. This exchange can be compared to two people constantly hitting a tennis ball back and forth. As long as this meson exchange is happening, the strong force holds the nucleons together. Neutrons also participate in the meson exchange and are even a bigger source of the strong force. Neutrons have no charge, so they approach other nuclei without adding an extra repulsive force; meanwhile, they increase the average distance between protons and help to reduce the repulsion between them within a nucleus.

#### 1.1.2.7 Nuclear Binding Energy and Mass Defect

It has been proved that the mass of a nucleus is always less than the sum of the individual masses of the constituent protons and neutrons (*mass defect*). The strong nuclear force is the result of the mass defect phenomenon. Using Einstein's mass energy relationship, the nuclear *binding energy* can be given as follows:

$$E_b = \Delta m.c^2$$

where $\Delta m$ is the mass defect, and $c$ is the speed of light in a vacuum.

The *average binding energy* per nucleon is a measure of nuclear stability. The higher the average binding energy is, the more stable the nucleus is.

**Table 1.1** Mass and charge of a proton, neutron, and electron

| Particle | Symbol | Charge[a] | Mass[b] | Mass (kg) | Energy (MeV) | Relative mass |
|---|---|---|---|---|---|---|
| Proton | p | +1 | 1.007276 | $1.6726 \times 10^{-27}$ | 938.272 | 1,836 |
| Neutron | n | 0 | 1.008665 | $1.6749 \times 10^{-27}$ | 939.573 | 1,839 |
| Electron | $e^-$ | −1 | 0.000548 | $9.1093 \times 10^{-31}$ | 0.511 | 1 |

[a] Unit charge $= 1.6 \times 10^{-19}$ coulombs
[b] Mass expressed in universal mass unit (mass of 1/12 of ${}^{12}C$ atom)
Data from Particles and Nuclei (1999)

### 1.1.3 Radioactivity

For all practical purposes, the nucleus can be regarded as a combination of two fundamental particles: neutrons and protons. These particles are together termed *nucleons*. The stability of a nucleus depends on at least two different forces: the repulsive coulomb force between any two or more protons and the strong attractive force between any two nucleons (nuclear forces). The nuclear forces are strong but effective over short distances, whereas the weaker coulomb forces are effective over longer distances. The stability of a nucleus depends on the arrangement of its nucleons, particularly the ratio of the number of neutrons to the number of protons. An adequate number of neutrons is essential for stability. Among the many possible combinations of protons and neutrons, only around 260 nuclides are stable; the rest are unstable.

It seems that there are favored neutron-to-proton ratios among the stable nuclides. Figure 1.1 shows the function of number of neutron (N) against the number of protons (Z) for all available nuclides. The stable nuclides gather around an imaginary line, which is called the *line of stability*. For light elements ($A < 50$), this line corresponds to $N = Z$, but with increasing atomic number the neutron-to-proton ratio increases up to 1.5 ($N = 1.5Z$). The line of stability ends at $A = 209$ (Bi), and all nuclides above that and those that are not close to this line are unstable. Nuclides that lie on the left of the line of stability (area I) have an excess of neutrons, those lying on the right of the line (area II) are neutron deficient, and those above the line (area III) are too heavy (excess of both neutrons and protons) to be stable.

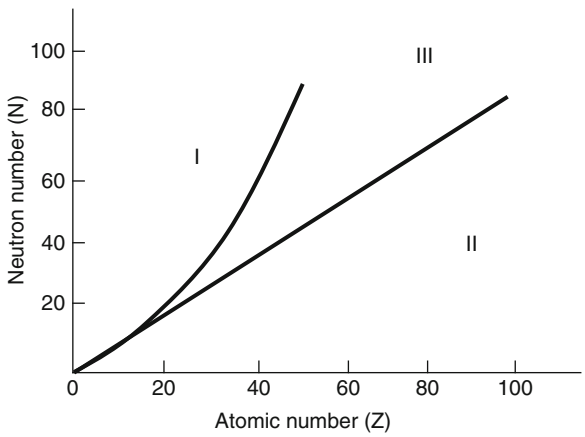


**Fig. 1.1** The line of stability and different regions around it. (Reproduced from [3])

An unstable nucleus sooner or later (nanoseconds to thousands of years) changes to a more stable proton-neutron combination by emitting particles such as alpha, beta, and gamma. The phenomenon of spontaneous emission of such particles from the nucleus is called *radioactivity,* and the nuclides are called *radionuclides*. The change from the unstable nuclide (parent) to the more stable nuclide (daughter) is called *radioactive decay* or *disintegration*. During disintegration, there is emission of nuclear particles and release of energy. The process is spontaneous, and it is not possible to predict which radioactive atom will disintegrate first.

#### 1.1.3.1 Modes of Decay

The radionuclide, which decays to attain stability, is called the *parent* nuclide, and the stable form so obtained is called the *daughter*. There are situations when the daughter is also unstable. The unstable nuclide may undergo transformation by any of the following modes.

##### Nuclides with Excess Neutrons

###### *Beta Emission*

Nuclides with an excess number of neutrons acquire a stable form by converting a neutron to a proton. In this process, an electron (negatron or beta minus) and an antineutrino are emitted. The nuclear equation is given as follows:

$$n \rightarrow p + e + \overline{\nu} + Energy$$

where n, p, e, and $\overline{\nu}$ represent the neutron, the proton, the negatron (beta minus), and the antineutrino, respectively. The proton stays in the nucleus, but the electron and the antineutrino are emitted and carry the released energy as their kinetic energy. In this mode of decay, the atomic number of the daughter nuclide is one more than that of the parent with no change in mass number. The mass of the neutron is more than the sum of masses of the proton, electron, and the antineutrino (the daughter is lighter than the parent). This defect in mass is converted into energy and randomly

shared between the beta particle and the antineutrino. Hence, the beta particle may have energy between zero to a certain maximum level (continuous spectrum). The antineutrino has no mass and charge and has no clinical application.

Radionuclides in which the daughter acquires a stable state by emitting beta particles only are called pure beta emitters, such as $^{3}H$, $^{14}C$, $^{32}P$, and $^{35}S$. Those that cannot attain a stable state after beta emission and are still in the excited states of the daughter emit gamma photons, either in a single transition or through cascades emitting more than one photon before attaining a stable state. $^{131}I$, $^{132}Xe$, and $^{60}Co$ emit beta particles followed by gamma emissions.

## Nuclides that lack Neutrons

There are two alternatives for the nucleus to come to a stable state:

1. Positron emission and subsequent emission of annihilation photons
   In this mode of decay, a proton transforms to a neutron, a positron, and a neutrino.

$$p \rightarrow n + e + v$$

   The neutron stays in the nucleus, but a positron and a neutrino are ejected, carrying the emitted energy as their kinetic energy. In this mode of decay, the atomic number of the daughter becomes one less than that of the parent with no change in mass number. The mass of the proton is less than the masses of the neutron, the positron, and the neutrino. The energy for creation of this mass ($E > 1.022$ MeV) is supplied by the whole nucleus. The excess energy is randomly shared by the positron and the neutrino. The energy spectrum of the positron is just like that of the beta particle (from zero to a certain maximum). The neutrino has no mass and charge and is of no clinical relevance. Some of the positron-emitting radionuclides are $^{11}C$, $^{13}N$, $^{15}O$, and $^{18}F$.
   Just a few nanoseconds after its production, a positron combines with an electron. Their masses are converted into energy in the form of two equal-energy photons (0.511 MeV each), which leave the site of their creation in exactly opposite directions. This phenomenon is called the *annihilation reaction,* and the photons so created are called *annihilation photons.*
2. Electron captures
   A nucleus with excess protons has an alternative way to acquire a stable configuration by attracting one of its own electrons (usually the k electron) to the nucleus. The electron combines with the proton, producing a neutron and a neutrino in the process.

$$p + e \rightarrow n + v$$

   The electron capture creates a vacancy in the inner electron shell, which is filled by an electron from the outer orbit, and characteristic radiation is emitted in the process. These photons may knock out orbital electrons. These electrons are called *Auger electrons* and are extremely useful for therapeutic applications (targeted therapy) due to their short range in the medium.
   Electron capture is likely to occur in heavy elements (those with electrons closer to the nucleus), whereas positron emission is likely in lighter elements. Radionuclides such as $^{67}Ga$, $^{111}In$, $^{123}I$, and $^{125}I$ decay partially or fully by electron capture.

## Nuclides with Excess Protons and Neutrons

There are two ways for nuclides with excess protons and neutrons (region III) to become more stable:

1. Alpha decay
   There are some heavy nuclides that get rid of the extra mass by emitting an alpha particle (two neutrons and two protons). The atomic number of the daughter in such decay is reduced by two and mass number is reduced by four. The alpha particle emission may follow with gamma emission to enable the daughter nucleus to come to its ground or stable state. Naturally occurring radionuclides such as $^{238}U$ and $^{232}Th$ are alpha emitters.
2. Fission
   It is the spontaneous fragmentation of very heavy nuclei into two lighter nuclei, usually with the emission of two or three neutrons. A large amount of energy (hundreds of million electron volts) is also released in this process. Fission nuclides themselves have no clinical application, but some of their fragments are useful. The fissile nuclides can

be used for the production of carrier free radioisotopes with high specific activity.

## Gamma Radiation and Internal Conversion

When all the energy associated with the decay process is not carried away by the emitted particles, the daughter nuclei do not acquire their ground state. Such nuclei can be in either an excited state or a metastable (isomeric) state. In both situations, the excess energy is often released in the form of one or more gamma photons. The average lifetime of excited states is short, and energy is released within a fraction of a nanosecond. The average lifetime of metastable states is much longer, and emission may vary from a few milliseconds to few days or even longer. During this period, the nucleus behaves as a pure gamma-emitting radionuclide. Some of the metastable states have great clinical application. The transition of a nucleus from a metastable state to a stable state is called an *isomeric transition*. The decay of $^{99m}$Tc is the best example of isomeric transition. The decay scheme of $^{99}$Mo-$^{99m}$Tc is shown in Fig. 1.2.

There are situations when the excited nuclei, instead of emitting a gamma photon, utilize the energy in knocking out an orbital electron from its own atom. This process is called *internal conversion,* and the emitted electron is called a *conversion electron*. The probability of K conversion electron is more than L or M conversion electrons, and the phenomenon is more common in heavy atoms. The internal conversion is followed by emission of characteristic x-rays or Auger electrons as the outer shell electrons move to fill the inner shell vacancies.

It should be noted that there is no difference between an x-ray and a gamma ray of equal energy except that the gamma ray originates from the nucleus and has a discrete spectrum of energy, whereas x-ray production is an atomic phenomenon and usually has a continuous spectrum.

## Laws of Radioactivity

There is no information available by which one can predict the time of disintegration of an atom; the interest really should not be in an individual atom because even an extremely small mass of any element consists of millions of identical atoms. Radioactive decay has been found to be a spontaneous process

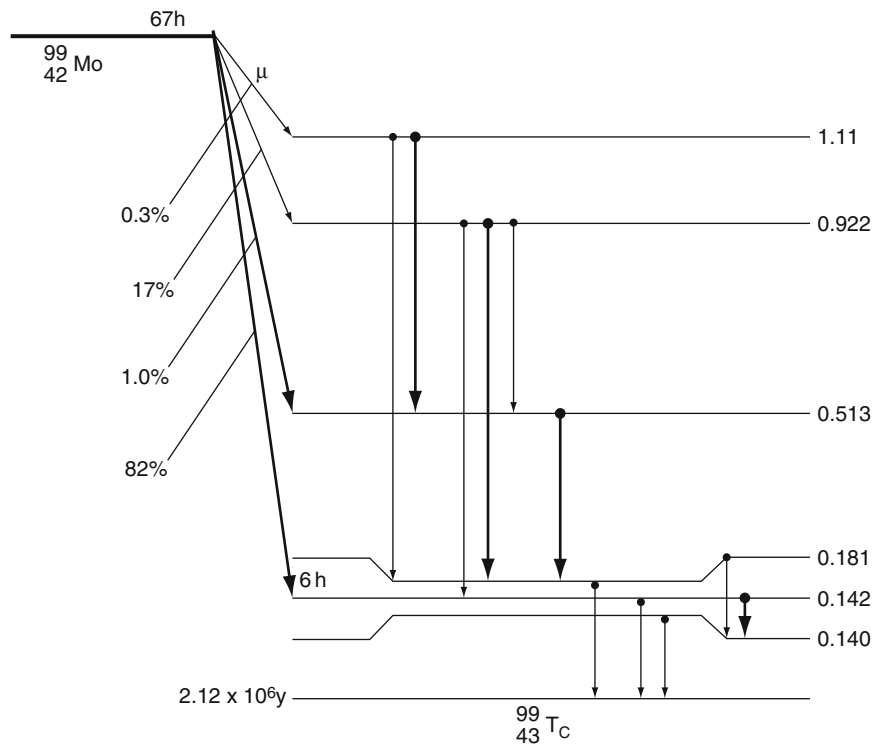


**Fig. 1.2** Decay scheme of $^{99}$Mo. (Reproduced from [3])

independent of any environmental factor. In other words, nothing can influence the process of radioactive disintegration. Radioactive decay is a random process and can be described in terms of probabilities and average constants.

In a sample containing many identical radioactive atoms, during a short period of time $(\partial t)$ the number of decayed atoms $(\partial N)$ is proportional to the total number of atoms $(N)$ present at that time. Mathematically, it can be expressed as follows:

$$-\partial N \propto N\partial t$$
$$-\partial N = \lambda N\partial t \tag{1.4}$$

or

$$\frac{\partial N}{\partial t} = -\lambda N$$

In this equation, the constant $\lambda$ (known as the *decay constant*) has a characteristic value for each radionuclide. The decay constant is the fraction of atoms undergoing decay per unit time in a large number of atoms. Its unit is the inverse of time.

For simplicity, the decay constant can be defined as the probability of disintegration of a nucleus per unit time. Thus, $\lambda = 0.01$ per second means that the probability of disintegration of each atom is 1% per second. It is important to note that this probability does not change with time.

The exact number of parent atoms in a sample at any time can be calculated by integrating Eq. 1.4, which takes the following form:

$$N = No * \exp(-\lambda t) \tag{1.5}$$

where *No* is the initial number of atoms in the sample, and $N$ is the number present at time $t$.

The term $\frac{\partial N}{\partial t}$ shows the number of disintegrations per unit time and is known as *activity*. The SI unit of activity is the becquerel (Bq; 1 decay per second). The conventional unit of activity is the curie (Ci), which is equal to $3.7 \times 10^{10}$ disintegrations per second (dps). This number $3.7 \times 10^{10}$ corresponds to the disintegrations from 1 g $^{226}$Ra.

## Half-Life

The time after which 50% of the atoms in a sample undergo disintegration is called the *half-life*. The half-life and decay constant are related by the following equation:

$$T_{1/2} = \frac{0.693}{\lambda} \text{ or } \lambda = \frac{0.693}{T_{1/2}} \tag{1.6}$$

## Average Life

The actual lifetimes of individual atoms in a sample are different; some are short, and some are long. The average lifetime characteristic of atoms is related to the half-life by

$$T_{av} = 1.44 \times T_{1/2} \tag{1.7}$$

The average life is a useful parameter for calculating the cumulated activity in the source organ in internal dosimetry.

## Radioactive Equilibrium

In many cases, the daughter element is also radioactive and immediately starts disintegrating after its formation. Although the daughter obeys the general rule of radioactive decay, its activity does not follow the exponential law of decay while mixed with the parent. This is because the daughter is produced (monoexponentially) by disintegration of its parent while it disintegrates (monoexponentially) as a radioactive element. So, the activity of such elements changes biexponentially: First the activity increases, then reaches a maximum, and then starts decreasing. The rate at which the activity changes in such a mixture of radionuclides depends on the decay constant of both the parent and the daughter.

If we start with a pure sample of a parent with a half-life of $T_1$ and a decay constant $\lambda_1$ and it contains $(N_1)_0$ atoms initially, the decay of this parent can be expressed by

$$N_1 = (N_1)_0 e^{-\lambda_1 t} \tag{1.8}$$

The rate of decay of the parent is the rate of formation of the daughter. Let the daughter decay at the rate $\lambda_2 N_2$, where $\lambda_2$ is the decay constant of the daughter

and $N_2$ is the number of atoms of the daughter. The net rate of formation of the daughter can be given by

$$\frac{\partial N_2}{\partial t} = \lambda_1 N_1 - \lambda_2 N_2 \tag{1.9}$$

The solution of this equation in terms of activity can be given as follows:

$$A_2 = A_1 \frac{T_1}{T_1 - T_2}\left(1 - e^{-0.693\left(\frac{T_1 - T_2}{T_1 T_2}\right)t}\right) \tag{1.10}$$

where $A_1$ and $A_2$ are the activity of the parent and daughter, respectively; $T_1$ and $T_2$ are their respective physical half-lives; and $t$ is the elapsed time. This equation is for a simple parent-daughter mixture. In general, three different situations arise from Eq. 1.10.

(a) Secular equilibrium
When the half-life of the parent ($T_1$) is too long in comparison to that of the daughter ($T_2$), Eq. 1.10 may be expressed as

$$A_2 = A_1\left(1 - e^{\frac{-0.693t}{T_2}}\right) \tag{1.11}$$

After one half-life of the daughter ($t = T_2$), $A_2$ will become nearly $A_1/2$; after two half-lives the daughter may grow up to three fourths of the parent, and after four half-lives (of the daughter) this increases to about 94% of the parent activity. Thus, activity of the daughter gradually increases, and after a few half-lives the activity of the parent and daughter become almost equal (Fig. 1.3); they are said to be in *secular equilibrium*.

(b) Transient equilibrium
The half-life of the parent is a few times ($\sim$ 10 times or more) longer than that of the daughter, but the difference is not as great as in secular equilibrium. In this case, the activity of the daughter increases and eventually slightly exceeds the activity of the parent to reach a maximum and then decays with the half-life of the parent, as can be seen in Fig. 1.4. For a large value of $t$, Eq. 1.10 can be written as

$$A_2 = A_1 \frac{T_1}{T_1 - T_2} \text{ for } t \gg T_2 \tag{1.12}$$

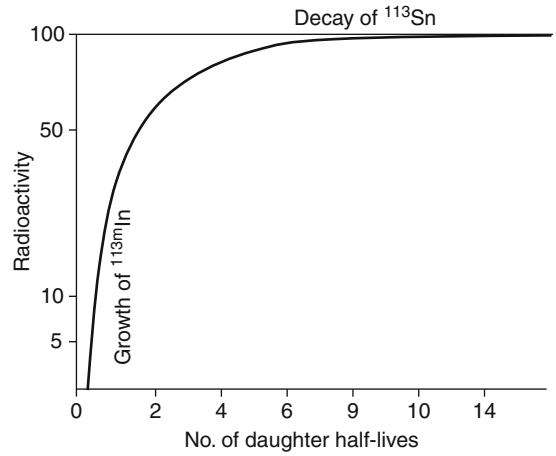


**Fig. 1.3** Secular equilibrium

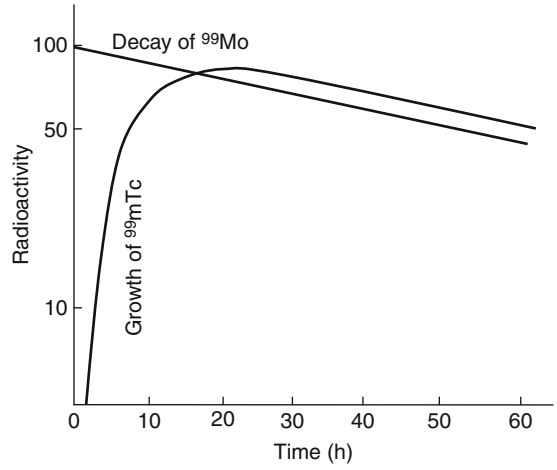


**Fig. 1.4** Transient equilibrium

The growth of the daughter for multiples of $T_2(T_2, 2T_2, 3T_2, 4T_2, etc.)$ will be nearly 50%, 75%, 87.5%, and 94%, respectively of the activity of the parent. It is therefore advisable to elute the activity from the technetium generator after every 24 h (Mo-99 with 67-h half-life and Tc-99m with 6-h half-life).

(c) No Equilibrium

If the half-life of the daughter is longer than the half-life of the parent, then there would be no equilibrium between them.

## 1.1.4 Interaction of Radiation with Matter

Ionizing radiation transfers its energy in full or part to the medium through which it passes by way of interactions. The significant types of interactions are excitation and ionization of atoms or molecules of the matter by charged particles and electromagnetic radiation (x-rays or gamma rays).

### 1.1.4.1 Interaction of Charged Particles with Matter

The charged particle loses some of its energy by the following interactions:

1. Ejection of electrons from the target atoms (ionization)
2. Excitation of electrons from a lower to a higher energy state
3. Molecular vibrations along the path (elastic collision) and conversion of energy into heat
4. Emission of electromagnetic radiation

In the energy range of 10 KeV to 10 MeV, ionization predominates over excitation. The probability of absorption of charged particles is so high that even a thin material can stop them completely.

The nature of the interaction of all charged particles in the energy range mentioned is similar. Light particles such as electrons deflect at larger angles than heavier particles, and there is a wide variation in their tortuous path. The path of a heavier particle is more or less a straight line. When electrons are deflected at large angles, they transfer more energy to the target atom and eject electrons from it. These electrons, while passing through the medium, produce secondary electrons along their track (delta rays). The charged particles undergo a large number of interactions before they come to rest. In each interaction, they lose a small amount of energy, and the losses are called *collision losses*.

Energetic electrons can approach the nucleus, where they are decelerated and produce bremsstrahlung radiation (x-rays). The chance of such an interaction increases with an increase in electron energy and the atomic number of the target material. Loss of electron energy by this mode is termed *radiative loss*. The energy lost per unit path length along the track is known as the *linear energy transfer* (LET) and is generally expressed in kilo-electron-volts per micrometer.

### 1.1.4.2 Range of a Charged Particle

After traveling through a distance in the medium, the charged particle loses all its kinetic energy and comes to rest as it has ample chance to interact with electrons or the positively charged nucleus of the atoms of the medium. The average distance traveled in a given direction by a charged particle is known as its *range* in that medium and is influenced by the following factors:

1. Energy. The higher the energy of the particle is, the larger is the range.
2. Mass. The higher the mass of the charged particle is, the smaller is the range.
3. Charge. The range is inversely proportional to the square of the charge.
4. Density of the medium. The denser the medium is, the shorter is the range of the charged particle.

### 1.1.4.3 Interaction of Electromagnetic Radiation with Matter

When a beam of x-rays or gamma rays passes through an absorbing medium, some of the photons are completely absorbed, some are scattered, and the rest pass through the medium almost unchanged in energy and direction (transmission). The transferred energy results in excitation and ionization of atoms or molecules of the medium and produces heat. The attenuation of the beam through a given medium is summarized as follows:

- The thicker the absorbing material is, the greater is the attenuation.
- The greater the atomic number of the material is, the greater is the attenuation.
- As the photon energy increases, the attenuation produced by a given thickness of material decreases.

#### 1.1.4.4 Linear Attenuation Coefficient

The linear attenuation coefficient $\mu$ is defined as the fractional reduction in the beam per unit thickness as determined by a thin layer of the absorbing material.

$$\mu = \frac{\text{Fractional reduction in a thin layer}}{\text{Thickness of the layers (cm)}}$$

The unit of the $\mu$ is $\text{cm}^{-1}$.

#### 1.1.4.5 Exponential Attenuation

The exponential law can explain the attenuation of radiation beam intensity. The mathematical derivation is given next.

Let $N_o$ be the initial number of photons in the beam and $N$ be the number recorded by the detector placed behind the absorber (Fig. 1.5).

The number $\delta N$, which gets attenuated, will be proportional to the thickness $\delta x$ of the absorber and to the number of photons $N$ present in the beam. The number $\delta N$ will depend on the number of atoms present in the beam and the thickness of the absorber.

Mathematically,

$$\begin{aligned} \delta N &\propto N.\,\delta x \\ \text{or } \delta N &= -\mu.N.\delta x \end{aligned} \tag{1.13}$$

where $\mu$ is a constant called the *linear attenuation coefficient* for the radiation used.

The negative sign indicates that as $\delta x$ increases, the number of photons in the beam decreases. Equation 1.13 can be rearranged as follows:

$$\mu = \frac{\delta N}{N.\delta x} \tag{1.14}$$

The formal definition of attenuation coefficient is derived from the integration of Eq. 1.14, which gives the following relationship:

$$N = No.\,e^{-\mu x} \tag{1.15}$$

Equation 1.15 can also be expressed in terms of beam intensity:

$$I = Io.\,e^{-\mu x} \tag{1.16}$$

where $I$ and $I_o$ are the intensities of the beam as recorded by the detector with and without absorbing material, respectively. The attenuation coefficient may vary for a given material due to nonuniform thickness. This is particularly so if the absorbing material is malleable. It is therefore better to express the mass absorption coefficient, which is independent of thickness of the absorbing material. The mass absorption coefficient is obtained by dividing the linear attenuation coefficient by the density of the material. The unit of the mass attenuation coefficient is square centimeters per gram. The electronic and atomic attenuation coefficients are also defined accordingly. The electronic attenuation coefficient is the fractional reduction in x-ray or gamma ray intensity produced by a layer of thickness 1 electron/$\text{cm}^2$, whereas the

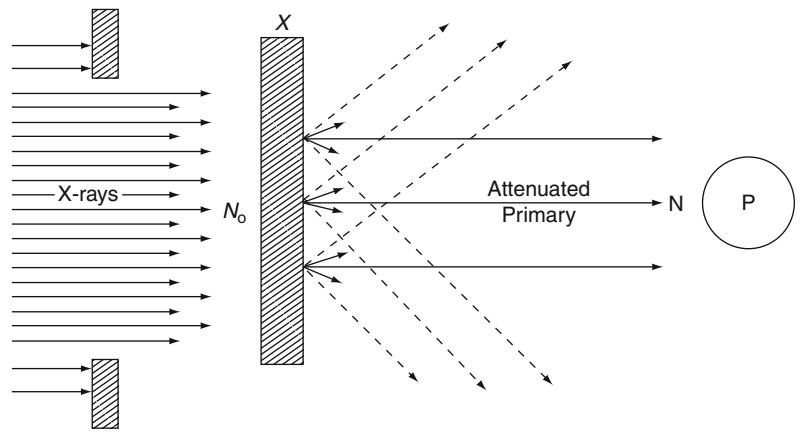


**Fig. 1.5** Attenuation of a radiation beam by an absorber. The transmitted beam is measured by detector P. (Reproduced from [4])

atomic attenuation coefficient is the fractional reduction by a layer of thickness 1 atom/cm$^2$. Thus, the atomic attenuation coefficient will be $Z$ times the electronic one.

#### 1.1.4.6 Half-Value Layer

From Eq. 1.16, it can be seen that, for a certain thickness ($x = d_{1/2}$) of the absorbing material, the intensity becomes half of its original value, that is, $I = I_o/2$. Substituting these values, Eq. 1.16 can be rearranged as follows:

$$d_{1/2}(HVL) = 0.693/\mu \tag{1.17}$$

The half-value layer or thickness (HVL or HVT) can be defined as the thickness of an absorbing material that reduces the beam intensity to half of its original value. Depending on the energy of radiation, various materials are used for the measurement of HVL, such as aluminum, copper, lead, brick, and concrete. The HVL for a broad beam is more than that for a narrow beam.

#### 1.1.4.7 Mechanism of Attenuation

There are many modes of interaction between a photon and matter, but only the types discussed next are of importance to us.

##### Photon Scattering

Photon scattering may or may not result in transfer of energy during the interaction of the photon with an atom of the medium.

##### Elastic Scattering

In elastic scattering or unmodified scattering, the photons are scattered in different directions without any loss of energy. The process thus attenuates the beam without absorption. In this process, the photon interacts with a tightly bound electron in an atom. The electron later releases the photon in any direction without absorbing energy from it. The contribution of this mode of interaction is relatively insignificant in medical applications of radiation. However, it has application in x-ray crystallography.

##### Inelastic (Compton) Scattering

Compton elucidated the mechanism of inelastic (Compton) scattering. In this process, the photon interacts with loosely bound (free) electrons. Part of the energy of the photon is used in ejecting the electron, and the rest is scattered in different directions (Fig. 1.6).

In a so-called head-on collision, the photon turns back along its original track (scattered through 180°), and maximum energy is transferred to the recoil electron. The change in wavelength $\delta\lambda$ of the photon is given by

$$\delta\lambda = 0.024(1 - \cos\varphi)\text{Å} \tag{1.18}$$

where $\varphi$ is the angle of scattering of the gamma photon, and Å is the angstrom unit for wavelength. The energy of the scattered photon is expressed as follows:

$$E_1 = E_0/[1 + E_0/m_e c^2\{1 - \cos\varphi\}] \tag{1.19}$$

where $E_0$ is the energy of the incident photon and $E_1$ is that of the scattered photon, $m_e$ is the mass of the electron, and c is the velocity of light in a vacuum. Compton scattering involves interaction between photons and electrons. The probability therefore depends on the number of electrons present and independent of the atomic number. With the exception of hydrogen, all elements contain nearly the same number of electrons per gram (practically the same electron density). Compton scattering, therefore, is

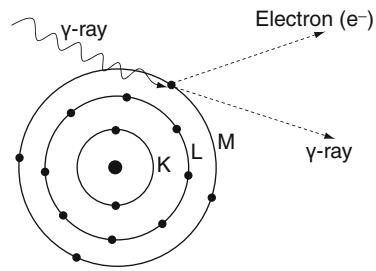


**Fig. 1.6** Process of Compton scattering. The incoming photon ejects the electron from outer orbit and is scattered with reduced energy in a different direction. (Reproduced from [4])

independent of atomic number. This is the choice of interaction required in radiation oncology, for which the delivered dose is homogeneous in spite of tissue inhomogeneity within the body.

The total probability $\sigma$ for the Compton process is given by

$$\sigma \quad = \sigma_s + \sigma_a$$

where $\sigma_s$ and $\sigma_a$ are the probabilities for scattering and absorption, respectively.

### 1.1.4.8 Photoelectric Effect

In the PEE process, the photon disappears when it interacts with the bound electron. The photon energy has to be higher than the binding energy of the electron for this type of interaction to take place.

$$\text{hv} = \text{BE} + \text{kinetic energy}$$

where hv is the energy of the photon and BE is the binding energy of the electron in the shell (Fig. 1.7). If the photon energy is slightly higher than the binding energy (BE), then the chance of PEE is high. For example, a photon of energy 100 keV has a high probability of undergoing PEE when it interacts with a Pb atom, for which the K shell binding energy is 88 keV. The rest of the (100 to 88) 12-keV energy will be carried away by the ejected electron as its kinetic energy. The ejection of the electron creates a hole in the inner shell, which is filled by an electron from any of the outer shells. Since the electrons in the outer shells possess higher energy than those in the inner shells, the difference in their energy is released as x-ray photons. Such photons are characteristic of the atom from which they are emitted. The K, L, M, and so on shells of a given atom have fixed energy, so the difference in their energies is also fixed. The radiation emitted therefore is termed the *characteristic x-rays*.

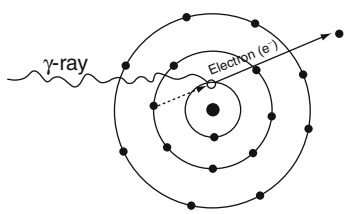


**Fig. 1.7** Process of photoelectric absorption. The incoming photon disappears (is absorbed), and the orbital electron is knocked out. An electron from the outer shell falls (*dotted line*) into the inner shell to fill the vacancy. (Reproduced from [4])

Three types of possibilities exist during PEE:

1. Radiative transitions
   As explained, during the electron transition from the outer orbit to the inner orbit, a photon is emitted with energy equal to the difference of the binding energies of the orbits involved. The vacancy moves to a higher shell; consequently, a characteristic photon of lower energy follows. The probability of emission of a photon is expressed as the fluorescent yield:

$$\text{Fluorescent yield} = \frac{\text{Number of x} - \text{ray photons emitted}}{\text{Number of orbital vacancies created}}$$

   Mostly, it is the K shell that is responsible for fluorescent yield.

$$\text{K shell fluorescent yield } (\omega\text{k}) = \frac{\text{Number of K x} - \text{ray photons emitted}}{\text{Number of K shell vacancies}}$$

   The yield increases with an increase in atomic number.
2. Auger electrons
   The characteristic x-ray photon, instead of being emitted, can eject another orbital electron from the atom. These electrons are called Auger electrons (Fig. 1.8). The energy of the Auger electron is equal to the difference of the x-ray photon energy and the binding energy of the shell involved in the process. The process competes with radiative transition. The Auger yield is expressed as the ratio of electrons emitted due to vacancies in subshell i and the total number of atoms with a vacancy in subshell i.
3. Coster–Kronig electrons
   The process for Coster–Kronig electrons is exactly like the Auger transition except that the electron filling the vacancy comes from the subshell of the same principal shell in which the vacancy lies. The kinetic energy of the emitted electrons can be calculated exactly as for Auger electrons. The energy

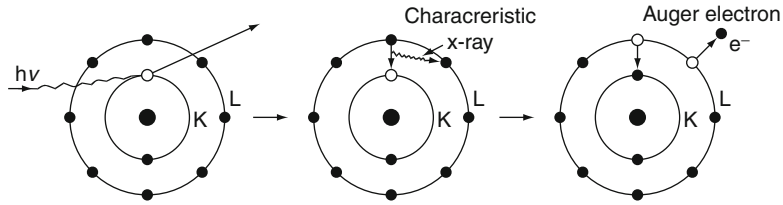


**Fig. 1.8** Mechanism of Auger electron emission. (Reproduced from [4])

of Coster–Kronig electrons is so small that they are quickly absorbed in the medium.

#### 1.1.4.9 Pair Production

When a photon with energy in excess of 1.022 MeV passes close to the nucleus of an atom, it may disappear, and in its place two antiparticles (negatron and positron) may be produced as shown in Fig. 1.9. In this process, energy converts into mass in accordance with Einstein's mass energy equivalence ($E = mc^2$). After traversing some distance through the medium, the positron loses its energy, combines with an electron, and annihilates. During combination, both the antiparticles disappear (annihilation) and two 0.511-MeV photons are emitted in the opposite direction.

#### 1.1.4.10 Photonuclear Reaction

When photon energy is too high, either a neutron or a proton may be knocked out (more likely the neutron) from the nucleus. For the majority of atoms, the threshold energy for this effect is more than 10 MeV, and the probability increases with increasing energy until a maximum is reached; above this maximum, the probability falls rapidly.

## 1.2 Radiation Safety

The applications of radiopharmaceuticals for medical diagnosis and therapy have rapidly increased due to the favorable physical characteristics of artificially produced radionuclides, progress in instrumentation, and computer technology. Efforts are under way to develop newer radiopharmaceuticals in nuclear medicine for both diagnostic and therapeutic procedures.

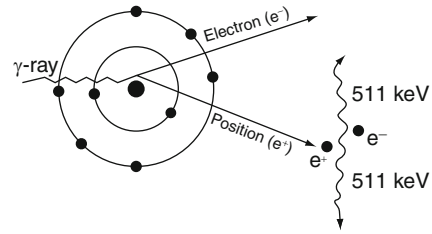


**Fig. 1.9** Schematic representation of pair production. (Reproduced from [4])

While such enthusiasm is appreciable, adequate safeguards against radiation exposure are also necessary to minimize the radiation risk to occupational workers, patients, and the public.

### 1.2.1 Types of Exposure

The following three categories of people are likely to be involved in radiation exposure in medical applications of ionizing radiation**:**

1. Occupational staff
2. Patients
3. Public

Protection is aimed at achieving a dose as low as reasonably achievable (ALARA) to these categories of people. Spending a minimum of *time* near the radiation sources, keeping a *distance* from them, and using *shielding* devices are the cardinal parameters for radiation safety. The fourth parameter with unsealed sources in nuclear medicine is to avoid or minimize the chance of *contamination.*

For safe use of radionuclides in nuclear medicine, the following basic requirements should be met:

1. The nuclear medicine facility should be well planned with a sufficient number of rooms for intended operations (including the storage and

disposal of radioactive waste) as approved by the competent authority.
2. All the equipment required for safe handling should be available in each room for proposed operations.
3. The staff should be adequate and well trained in handling radioactive material.
4. Radiation monitoring instruments (survey meters, contamination monitors, pocket dosimeters, digital monitors etc.) and decontamination facility should be readily available.

#### 1.2.1.1 Protection of Staff

Nuclear medicine procedures demand preparation of radiopharmaceuticals, their internal movement within the facility, and finally administration to the patient. At each step, there is a possibility of radiation exposure if safety guidelines are ignored. The diagnostic procedures normally do not cause any alarming exposure to the staff and public. However, patients administered radioactive substances for therapeutic purposes become a source of radiation to the staff and their attendants and public. Therapeutic radionuclides are usually beta emitters that do not pose much of a problem from a safety standpoint, and patients treated with them can even be treated as outpatients. However, patients treated with radioiodine (I-131) need hospitalization if treated beyond a certain dose as per national regulatory requirements due to penetrating gamma radiation. These patients stay in a specifically designed isolation room or ward until the body burden decreases to an acceptable level for release from the hospital.

#### Work Practice

Good work practice is an essential component of radiation safety. This includes observation of all radiation protection rules as applicable to nuclear medicine, use of appropriate safety devices, remote handling of tools/accessories, and maintaining good housekeeping habits in the laboratory.

In addition to the external irradiation, there is a chance of radioactive contamination while handling unsealed sources in nuclear medicine procedures. The radioactive waste generated during preparation, dispensing, and administration of radiopharmaceuticals shall be handled carefully to minimize exposure to staff and the public.

#### 1.2.1.2 Protection of Patients

Every practice involving ionizing radiation should be justified in terms of net positive benefit. It is particularly important for children, for whom long-term risks of exposure to ionizing radiation are larger. Once clinically justified, each examination involving ionizing radiation should be conducted such that the radiation dose to the patient is the lowest necessary to achieve the clinical aim (optimization). Reference and achievable doses for various radionuclide investigations have been proposed for this purpose by various organizations. The concept of reference doses is recognized as a useful and practical tool for promoting the optimization of patient protection. While reducing the radiation dose to the patient, image quality should not be compromised, which may otherwise lead to repeat investigation. Routine quality control (QC) tests of imaging systems and radiopharmaceuticals have to be done before clinical studies. Another consideration in reducing the patient dose is to avoid misadministration and to provide proper radiation counseling to patients and their family or others involved.

#### What Is Misadministration?

Error in any part of the procedure starting from patient selection to the interpretation of final results may lead to a repeat study. This in turn leads to an increased radiation dose not only to the patient but also to the staff. A major contributor to increased radiation dose to the patient is misadministration. Misadministration has several components, such as administration of the wrong radiopharmaceutical or the wrong dose or giving the dose to a wrong patient or through a wrong route, which ultimately lead to undesirable exposure to a patient.

The following points should be checked to avoid misadministration:

*Identity of the patient*: The radiopharmaceutical should be administered to the patient for whom it is prepared. Name, age, and medical record number should be checked before dose administration.

*Radionuclide and its physical or chemical form*: The physical and chemical form of the radiopharmaceutical should be reconfirmed before administration. Radiopharmaceuticals should go through routine QC procedures to check for any inadequate preparation.

*Dose, quantity of radioactivity, QC*: The radioactivity should be measured in a dose calibrator before administration. The accuracy and precision of the radionuclide dose calibrator need to be maintained at all times for accuracy in dose estimation. Similarly, imaging equipment should be maintained at its optimum level of performance.

*Route*: The physician should confirm the route of administration (oral, intravenous) of the radiopharmaceutical.

*Pregnancy and breast feeding*: Female patient should notify if she is pregnant or breast feeding. This can happen with proper patient education.

Proper counseling is also helpful in reducing exposure to patients and their family members.

#### 1.2.1.3 Protection of the Public or Environment

To ensure that unnecessary exposure to the members of the public is avoided, the following guidelines shall be followed:

1. No member of the public shall be allowed to enter the controlled (hot laboratory and the injection room/area, imaging rooms) and supervised (consoles) areas.
2. Appropriate warning signs and symbols shall be posted on doors to restrict access.
3. Relatives or friends of the patients receiving therapeutic doses of radioactive iodine shall not be allowed to visit the patient without the permission of the radiation safety officer (RSO). The visitors shall not be young children or pregnant women.
4. A nursing mother who has been administered radiopharmaceuticals shall be given instructions to be followed at home after her release from the hospital. The breast-feeding may have to be suspended.
5. An instruction sheet shall be given at the time of release from the hospital to patients administered therapeutic doses of radioiodine; the instructions should be followed at home for a specified period as suggested by the RSO.
6. The storage of radioactive waste shall be done at a location within the hospital premises with adequate shielding to eliminate the public hazard from it.

### 1.2.2 Control of Contamination

Radioactive contamination can be minimized by carefully designing the laboratory, using proper handling tools, and following correct operating procedures together with strict management and disposal of radioactive waste. In the event of contamination, procedures indicated should be followed to contain the contamination.

#### 1.2.2.1 Management of a Radioactive Spill

1. Perform a radiation and contamination survey to determine the degree and extent of contamination.
2. Isolate the contaminated area to avoid spread of contamination. No person should be allowed to enter the area.
3. Use gloves, shoe covers, lab coat, and other appropriate clothing.
4. Rapidly define the limits of the contaminated area and immediately confine the spill by covering the area with absorbent materials with plastic backing.
5. First remove the "hot spots" and then scrub the area with absorbent materials, working toward the center of the contaminated area. Special decontamination chemicals (Radiacwash) shall be used in the case of a severe spill.
6. All personnel should be surveyed to determine contamination, including their shoes and clothing. If the radioactive material appears to have become airborne, the nostrils and mouth of possible contaminated persons should be swabbed, and the samples shall be evaluated by the RSO.
7. Shut off ventilation if airborne activity is likely to be present (rare situation).
8. A heavily contaminated individual may take a shower in the designated decontamination facility as directed by the RSO. Disposable footwear and gloves should be worn in transit.
9. If significant concentrations of radioiodine have been involved, subsequent thyroid uptake

measurements should be made on potentially exposed individuals after 24 h.

10. Monitor the decontaminated area and all personnel leaving the area after the cleanup. Particular attention should be paid to checking the hands and the soles of shoes.
11. All mops, rags, brushes, and absorbent materials shall be placed in the designated waste container and should be surveyed by the RSO. Proper radioactive disposal should be observed.
12. The RSO should provide the final radiation survey report with necessary recommendations or advice to avoid such an incident in the future.

#### 1.2.2.2 Personnel Decontamination

Contaminated eyes

- If eye contamination is found, the eye should be flushed profusely with isotonic saline or water by covering other parts with a towel to prevent the spread of contamination. An ophthalmologist shall be consulted if there are signs of eye irritation.

Contaminated hair

- If hair is contaminated, try up to three washings with liquid soap and rinse with water.
- Prevent water from running onto the face and shoulders by shielding the area with towels.
- Perform a radiation survey.

Contaminated skin

- Remove any contaminated clothing before determining the level of skin contamination. Levels below 0.1 mR/h (1 μSv/h) are considered minimal hazards.
- If there is gross skin contamination, it shall be given attention first. Wipe with a cotton swab moistened with water and liquid soap using long forceps. Place all swabs in a plastic container for radiation level measurement and storage before disposal.
- If a large skin area is contaminated, the person should have a 10-min shower. Dry the body with a towel in the shower room and monitor the radiation level over the whole body. Do not allow any water to drip on the floor outside the shower room to avoid the spread of contamination.
- Place all the towels and other contaminated clothing in a plastic bag for later monitoring of radiation level for storage and decay.
- Specific hot spots on the skin can be localized with a survey meter or appropriate contamination monitor.
- Clean the specific areas with mild soap and warm water. Avoid using detergents or vigorous scrubbing for they might damage the skin. The use of a soft brush is adequate.
- For stubborn contamination, covering a contaminated area with plastic film or disposable cotton or latex gloves over a skin cream helps remove the contamination through sweating.

#### 1.2.2.3 Internal Contamination

- Simple expedients such as oral and nasopharyngeal irrigation, gastric lavage, or an emetic and use of purgatives may greatly reduce the uptake of a contaminant into the circulation.
- Blocking agents or isotopic dilution techniques can appreciably decrease the uptake of the radionuclides into relatively stable metabolic pools such as bone. These should be administered without delay.

When a contaminated person requires treatment (for wounds) by a physician, the emergency room (ER) should be informed. The following points must be remembered:

- Medical emergencies are the priority and must be attended first. Radiation injuries are rarely life threatening to the victim and the attending physician/staff.
- Clean the wound with mild detergent and flush with isotonic saline or water. If necessary, a topical anesthetic, such as 4% lidocaine, can be used to allow more vigorous cleansing. After a reasonable effort, there is no need to attempt to remove all contamination since it will probably be incorporated into the scab.
- Whenever radionuclides have entered the skin via a needle or sharps, induce the wound to bleed by "milking" it as a cleansing action in addition to the use of running water.
- Perform radiation monitoring at the surface.

### 1.2.3 Radioiodine Therapy: Safety Considerations

Radioiodine has been effectively used for more than five decades to ablate remnant thyroid tissue following thyroidectomy and for treating distant metastases. Looking at the radiation hazard to staff and the public, national regulatory bodies have established guidelines for the hospitalization and subsequent release of patients administered radioiodine from the hospital. The limit of body burden at which these patients are released from the hospital varies from country to country. Groups who may be critically exposed among the public are fellow travelers during the journey home after release from the hospital and children and pregnant women among other family members at home.

The administered dose of radioiodine is concentrated avidly by thyroidal tissue (thyroid remnant, differentiated thyroid cancer). It rapidly gets excreted via the kidney and urinary bladder and to a lesser extent through perspiration, saliva, exhalation, and the gut. The faster biological excretion of the activity in a thyroid cancer patient actually poses less radiation hazard to the environment than actually expected. Counseling of patients and family members from a radiation safety viewpoint is necessary before therapeutic administration.

#### 1.2.3.1 Radiation Monitoring

Routine monitoring of all work surfaces, overcoats, exposed body parts, and so on is essential before leaving the premises. Both Gieger-Muller (G.M.)-type survey meters and ionization chamber-type survey meters are required for monitoring. All persons involved in a radioiodine procedure should be covered by personnel radiation monitoring badges, and their neck counts should also be measured periodically. It is advisable to carry out periodic air monitoring in these areas to ensure that no airborne activity is present.

#### 1.2.3.2 Use of a Fume Hood

Radioiodine in capsule form poses much less radiation safety problems than in liquid form. When in liquid form, the vials containing I-131 should be opened only inside a fume hood using remote-handling bottle openers. If these vials are opened outside the fume hood, there is every possibility that the worker involved may inhale a fraction of the vaporous activity. All operations using I-131 should be carried out wearing face masks, gloves, and shoe covers and using remote-handling tools. Radioactive iodine uptake measurement for the thyroid of staff involved should be done weekly to check for any internal contamination.

#### 1.2.3.3 Specific Instructions to the Patient

It is the combined responsibility of the physician and the medical physicists or technologists to administer the desired dose to the patient. The patient is normally advised to come with an empty stomach or after a light breakfast and not to eat or drink anything for 1–2 h after therapeutic administration. After this time, they are advised to have as much fluids as possible for fast excretion of radioiodine from the kidneys. They are also advised to void the urinary bladder frequently and to flush the toilet twice after each voiding. This practice not only reduces the radiation dose to the kidneys, bladder, and entire body of the patients but also helps in their fast release from the hospital.

In female patients of reproductive age, two important aspects need to be considered:

1. Possibility of pregnancy: Radionuclide therapy is strictly prohibited during pregnancy.
2. Pregnancy after radionuclide therapy should be avoided for at least 4 months (4–6 months) or as advised by the treating physician.

#### 1.2.3.4 Discharge of the Patient from the Hospital

The regulatory authority of each country decides the maximum limit of activity of I-131 at which the patient may be discharged from the hospital. This can be roughly estimated by measuring the exposure rate from the patient at a 1-m distance with a calibrated survey meter, which should read approximately 50 μSv/h (5 mR/h) for a body burden of 30 mCi or less.