Electronic Structure of Atoms

Electrons in an atom are grouped around the nucleus into shells.

Shell (electron) : A grouping of electrons in an atom according to energy

The farther a shell is from the nucleus, the larger it is, the more electrons it can hold, and the higher the energies of those electrons.

The first shell (closest to the nucleus) can hold two electrons. The second shell can hold 8 electrons. The third shell can hold 32 electrons.
Electronic Structure of Atoms

Within the shells, electrons are further grouped into subshells of four different types, identified as s, p, d, and f in order of increasing energy. The first shell has only an s subshell; the second shell has an s and a p subshell; the third shell has s, p, and d subshells, and the fourth has s, p, d and f subshells. The number of subshells is equal to the shell number. A specific subshell is symbolized by writing the number of the shell, followed by the letter for the subshell.
Electronic Structure of Atoms

Subshell (electron): A grouping of electrons in a shell according to the shape of the region of space they occupy.

Within each subshell, electrons are grouped into orbitals, regions of space within an atom where the specific electrons are most likely to be found. Within each subshell, electrons are grouped into orbitals, regions of space within an atom where the specific electrons are most likely to be found. Each orbital holds two electrons which differ in a property known as spin.
• Orbital: A region of space within an atom where an electron in a given subshell can be found.

<table>
<thead>
<tr>
<th>Shell number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subshell designation</td>
<td>s</td>
<td>s, p</td>
<td>s, p, d</td>
<td>s, p, d, f</td>
</tr>
<tr>
<td>Number of orbitals</td>
<td>1</td>
<td>1, 3</td>
<td>1, 3, 5</td>
<td>1, 3, 5, 7</td>
</tr>
</tbody>
</table>

• Any orbital can hold a maximum of 2 electrons with opposite spin. The first shell has one 1s orbital and holds 2 electrons. The second shell holds 8 electrons; 2 in a 2s orbital and 6 in three 2p orbitals. The third shell holds 18 electrons; 2 in a 3s orbital; 6 in three 3p orbitals; and 10 in five 3d orbitals. The fourth shell holds 32 electrons; 2 in a 4s orbital; 6 in three 4p orbitals; 10 in five 4d orbitals; and 14 in seven 4f orbitals.
<table>
<thead>
<tr>
<th>SHELL NUMBER:</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
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<td>s</td>
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</tr>
<tr>
<td>Number of orbitals:</td>
<td>1</td>
<td>1, 3</td>
<td>1, 3, 5</td>
<td>1, 3, 5, 7</td>
</tr>
<tr>
<td>Number of electrons:</td>
<td>2</td>
<td>2, 6</td>
<td>2, 6, 10</td>
<td>2, 6, 10, 14</td>
</tr>
<tr>
<td>Total electron capacity:</td>
<td>2</td>
<td>8</td>
<td>18</td>
<td>32</td>
</tr>
</tbody>
</table>
Electron Configurations

The exact arrangement of electrons in an atom's shells and subshells is the atom's electron configuration. It can be predicted by applying three rules.

Electron Configuration: The specific arrangement of electrons in an atom's shell and subshells.

**Rule 1:** Electrons occupy the lowest energy orbitals, available. This is complicated by "crossover" of energies above the 3p level.

Below is a simple scheme to help remember the order in which the orbitals are filled.
• **Rule 2:** Each orbital can hold only two electrons, which must be of opposite spin.

• **Rule 3:** Two or more orbitals with the same energy are each half-filled by one electron before any one orbital is completely filled by addition of the second electron:

• The number of electrons in each subshell is indicated by a superscript.
8 electrons in second shell

2 electrons in first shell:  \[ 1s^2 \]

2 electrons in third shell

Mg (atomic number 12):  \[ 1s^2 \ 2s^2 \ 2p^6 \ 3s^2 \]

<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic Number</th>
<th>Electron Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1</td>
<td>1s^1</td>
</tr>
<tr>
<td>He</td>
<td>2</td>
<td>1s^2</td>
</tr>
<tr>
<td>Li</td>
<td>3</td>
<td>1s^2 2s^1</td>
</tr>
<tr>
<td>Be</td>
<td>4</td>
<td>1s^2 2s^2</td>
</tr>
<tr>
<td>B</td>
<td>5</td>
<td>1s^2 2s^2 2p^1</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>1s^2 2s^2 2p^2</td>
</tr>
<tr>
<td>N</td>
<td>7</td>
<td>1s^2 2s^2 2p^3</td>
</tr>
<tr>
<td>O</td>
<td>8</td>
<td>1s^2 2s^2 2p^4</td>
</tr>
<tr>
<td>F</td>
<td>9</td>
<td>1s^2 2s^2 2p^5</td>
</tr>
<tr>
<td>Ne</td>
<td>10</td>
<td>1s^2 2s^2 2p^6</td>
</tr>
<tr>
<td>Na</td>
<td>11</td>
<td>1s^2 2s^2 2p^6 3s^1</td>
</tr>
<tr>
<td>Mg</td>
<td>12</td>
<td>1s^2 2s^2 2p^6 3s^2</td>
</tr>
<tr>
<td>Al</td>
<td>13</td>
<td>1s^2 2s^2 2p^6 3s^2 3p^1</td>
</tr>
<tr>
<td>Si</td>
<td>14</td>
<td>1s^2 2s^2 2p^6 3s^2 3p^2</td>
</tr>
<tr>
<td>P</td>
<td>15</td>
<td>1s^2 2s^2 2p^6 3s^2 3p^3</td>
</tr>
<tr>
<td>S</td>
<td>16</td>
<td>1s^2 2s^2 2p^6 3s^2 3p^4</td>
</tr>
<tr>
<td>Cl</td>
<td>17</td>
<td>1s^2 2s^2 2p^6 3s^2 3p^5</td>
</tr>
<tr>
<td>Ar</td>
<td>18</td>
<td>1s^2 2s^2 2p^6 3s^2 3p^6</td>
</tr>
<tr>
<td>K</td>
<td>19</td>
<td>1s^2 2s^2 2p^6 3s^2 3p^6 4s^1</td>
</tr>
<tr>
<td>Ca</td>
<td>20</td>
<td>1s^2 2s^2 2p^6 3s^2 3p^6 4s^2</td>
</tr>
</tbody>
</table>
These are the electron configurations for B – N in which the 2p shell begins to fill.

\[
\begin{align*}
\text{B} & \quad 1s^2 \ 2s^2 \ 2p^1 \quad \text{or} \quad \frac{\uparrow \downarrow}{1s^2} \quad \frac{\uparrow \downarrow}{2s^2} \quad \frac{\uparrow}{2p^1} \quad \text{or} \quad [\text{He}] \ 2s^2 \ 2p^1 \\
\text{C} & \quad 1s^2 \ 2s^2 \ 2p^2 \quad \text{or} \quad \frac{\uparrow \downarrow}{1s^2} \quad \frac{\uparrow \downarrow}{2s^2} \quad \frac{\uparrow \uparrow}{2p^2} \quad \text{or} \quad [\text{He}] \ 2s^2 \ 2p^2 \\
\text{N} & \quad 1s^2 \ 2s^2 \ 2p^3 \quad \text{or} \quad \frac{\uparrow \downarrow}{1s^2} \quad \frac{\uparrow \downarrow}{2s^2} \quad \frac{\uparrow \uparrow \uparrow}{2p^3} \quad \text{or} \quad [\text{He}] \ 2s^2 \ 2p^3
\end{align*}
\]

These are the electron configurations for O – Ne in which the 2p shell is completed.

\[
\begin{align*}
\text{O} & \quad 1s^2 \ 2s^2 \ 2p^4 \quad \text{or} \quad \frac{\uparrow \downarrow}{1s^2} \quad \frac{\uparrow \downarrow}{2s^2} \quad \frac{\uparrow \uparrow \uparrow \uparrow}{2p^4} \quad \text{or} \quad [\text{He}] \ 2s^2 \ 2p^4 \\
\text{F} & \quad 1s^2 \ 2s^2 \ 2p^5 \quad \text{or} \quad \frac{\uparrow \downarrow}{1s^2} \quad \frac{\uparrow \downarrow}{2s^2} \quad \frac{\uparrow \uparrow \uparrow \uparrow}{2p^5} \quad \text{or} \quad [\text{He}] \ 2s^2 \ 2p^5 \\
\text{Ne} & \quad 1s^2 \ 2s^2 \ 2p^6 \quad \text{or} \quad \frac{\uparrow \downarrow}{1s^2} \quad \frac{\uparrow \downarrow}{2s^2} \quad \frac{\uparrow \uparrow \uparrow \uparrow}{2p^6}
\end{align*}
\]
• **NUCLEAR STRUCTURE**

• The *atom* consists of a small but massive *nucleus* surrounded by a cloud of rapidly moving *electrons*. The nucleus is composed of *protons and neutrons*. Total number of protons in the nucleus is called the *atomic number* of the atom and is given the *symbol Z*. The total electrical charge of the nucleus is therefore $+Ze$, where $e$ (elementary charge) equals to $1.602 \times 10^{-19}$ *coulombs*. In a neutral atom there are as many electrons as protons moving about nucleus. It is the electrons that are responsible for the chemical behavior of atoms, and which identify the various chemical elements.
• Hydrogen (H), for example, consists of one electron and one proton. The number of neutrons in a nucleus is known as

• **Atomic symbol the neutron number and is given the symbol**

• Abbreviation used N. The total number of nucleons, that is, protons and neutrons in a nucleus, is equal to \( Z + N = A \), where \( A \) is called the atomic mass number. The various species of atoms whose nuclei contain particular numbers of protons and neutrons are called **nuclides**. Each nuclide is denoted by chemical symbol of the element (this specifies \( Z \)) with the atomic mass number as superscript.

• Thus the symbol \(^1\text{H}\) refers to the nuclide of hydrogen with a single proton as nucleus. \(^2\text{H}\) is the hydrogen nuclide with a neutron as well as a proton.
Mass number
Number of protons and neutrons in atom

Atomic symbol
Abbreviation used to represent atom in chemical formulas

Atomic number
Number of protons in atom

\[ ^{12}_{6}C \]
6 protons
6 neutrons
6 electrons
• in the nucleus ($^2$H is also called deuterium or heavy hydrogen). Atoms such as $^1$H, $^2$H whose nuclei contain the same number of protons but different number of neutrons (different A) are known as isotopes.

• Uranium, for instance, has three isotopes occurring in nature: $^{238}$U, $^{235}$U and $^{234}$U. The stable isotopes (plus a few of the unstable isotopes) are the atoms that are found in the naturally occurring elements in nature. However, they are not found in equal amounts. Some isotopes of a given element are more abundant than others. For example 99.27% of naturally occurring uranium atoms are the isotope $^{238}$U, 0.72% is the isotope $^{235}$U and 0.0055% are the isotope $^{234}$U. Exact structure of atoms is described by Atomic Theory and Theory of Nuclear Structure.
• The volume of an atom is about 15 orders of magnitude larger than the volume of a nucleus. For uranium atom, the Van der Waals radius is about 186 pm = 1.86 *10^{-10} m.

• The Van der Waals radius, $r_w$, of an atom is the radius of an imaginary hard sphere representing for the distance of closest approach for another atom. Assuming spherical shape, the Uranium atom have volume of about $26.9 \times 10^{-30}$ m$^3$.

• But this "huge" space is occupied primarily by electrons, because the nucleus occupies only about $1721 \times 10^{-45}$ m$^3$ of space. These electrons together weigh only a fraction (let say 0.05%) of entire atom.
• **Mass Defect**

  • **Definition**: Mass defect refers to the difference in mass between an atom and the sum of the masses of the protons, neutrons, and electrons of the atom.
  
  • This mass is typically associated with the binding energy between nucleons.
  
  • Because of the strong nuclear force, the nucleons in a stable nucleus are held tightly together. Therefore, energy is required to separate a stable nucleus into its constituent protons and neutrons, as Figure below illustrates. The more stable the nucleus is, the greater is the amount of energy needed to break it apart. The required energy is called the binding energy of the nucleus,

  ![Diagram of binding energy](image)

  The figure shows that energy, called the binding energy, must be supplied to break the nucleus apart into its constituent protons and neutrons. Each of the separated nucleons is at rest and out of the range of the forces of the other nucleons, binding energy of a nucleus can be determined from the mass defect according to Equation:

  • **Binding Energy** = $\Delta mC^2$
• **Binding Energy**

Binding energy, amount of energy required to separate a particle from a system of particles or to disperse all the particles of the system. Binding energy is especially applicable to subatomic particles in atomic nuclei, to electrons bound to nuclei in atoms, and to atoms and ions bound together in crystals.
Nuclear binding energy is the energy required to separate an atomic nucleus completely into its constituent-protons and neutrons, or, equivalently, the energy that would be liberated by combining individual protons and neutrons into a single nucleus. The hydrogen-2 nucleus, for example, composed of one proton and one neutron, can be separated completely by supplying 2.23 million electron volts (MeV) of energy. Conversely, when a slowly moving neutron and proton combine to form a hydrogen-2 nucleus, 2.23 MeV are liberated in the form of gamma radiation. The total mass of the bound particles is less than the sum of the masses of the separate particles by an amount equivalent (as expressed in Einstein's mass-energy equation) to the binding energy.
Electron binding energy, also called ionization potential, is the energy required to remove an electron from an atom, a molecule, or an ion. In general, the binding energy of a single proton or neutron in a nucleus is approximately a million times greater than the binding energy of a single electron in an atom.

An atom is said to be ionized when one of its electrons has been completely removed. The detached electron is negative ion and the remnant atom a positive ion. Together they form an ion pair. The binding energy depends on the shell (\( E_K > E_L > E_M \)), and on the element, increasing as the atomic number increases.

An atom is excited when an electron is raised from one shell to another farther out.
Example: Let's assemble a helium-4 nucleus \(^4\text{He}\), also known as an alpha particle, and determine what its binding energy is. We need to know the rest masses of protons, neutrons and alpha particles:

- \( \text{P}^+ = 1.007277 \text{ u} \)
- \( n^0 = 1.008665 \text{ u} \)
- \( ^4\text{He} = 4.001506 \text{ u} \)

The mass of two protons and two neutrons is \(2(1.007277) + 2(1.008665) = 4.031884 \text{ u} \).

The difference in mass = calculated mass - actual mass = \(4.031884 - 4.001506 = 0.030378 \text{ u} \)

Now convert this mass into kg, and then, using Einstein's relation, convert this mass into energy:

\[
0.030378 \text{ u} \times 1.660531 \times 10^{-27} \text{ kg/u} \times (3.0 \times 10^8)^2 \text{ m/s} = 4.54 \times 10^{-12} \text{ kg. m}^2/\text{s}^2 = 4.54 \times 10^{-12} \text{ J.}
\]

Nuclear Instability

Radioactive decay occurs because a nuclei is unstable. It emits alpha particles, beta particles or gamma rays to become more stable.

Z is the proton number (sometimes called atomic number) it is the number or protons in the nucleus.
• A is the nucleon number (sometimes called mass number) it is the total number of protons AND neutrons in the nucleus.
• N is the number of neutrons = A - Z
• **Graph of N against Z**

- for light isotopes (up to Z=20) the stable nuclei have equal numbers of protons and neutrons.
- for heavier nuclie to be stable they need to have more neutrons than protons (see the line for stable isotopes on the graph above).
- nuclei which are unstable lie either side of the stability line.
- nuclei with too many protons are to the right of the stability line and become more stable by emitting a beta+ (b⁺) particle when a proton converts into a neutron.
• Nuclei with too few protons are to the left of the stability line and become more stable by emitting a beta- (b)particle when a neutron converts into a proton.

• **How nuclei change when they decay**

![Diagram](image)

**Alpha decay:**
- In alpha decay the unstable parent nuclei emits an alpha particle (2 protons and 2 neutrons) so the daughter nuclei has 2 less protons and 2 less neutrons.
- \[ ^{232}_{90}Th \longrightarrow ^{228}_{88}Ra + \frac{4}{2}\alpha \]

**Beta-(β-) decay:**
- In the parent nuclei a neutron changes into a proton and emits a beta- B-particle (electron). So the daughter nuclei has one less neutron and one more proton.
- \[ ^{228}_{88}Ra \longrightarrow ^{228}_{89}Ac + ^{0}_{1}\beta \]
• **Beta+ (β+) decay**
  In the parent nuclei a proton changes into a neutron and emits a beta+ B+ particle (positron). So the daughter nuclei has one less proton and one more neutron.

  \[
  ^{22}_{11}\text{Na} \rightarrow ^{22}_{10}\text{Ne} + ^{0}_{+1}\beta
  \]

• **Electron capture**
  In electron capture a proton captures and orbiting electron and the combines to form a neutron. So the daughter nuclei has one less proton and one more neutron.

  \[
  ^{51}_{24}\text{Cr} + ^{0}_{-1}\text{e} \rightarrow ^{51}_{23}\text{V}
  \]

• **Gamma ray emission**
  Gamma ray emission may happen at the same time as alpha or beta decay or it may occur a short while after. The nuclei become more stable in gamma ray emission by emitting a photon. There is no change in the number of protons or neutrons when a gamma ray is emitted.

  \[
  ^{241}_{95}\text{Am} \rightarrow ^{237}_{93}\text{Np} + ^{4}_{2}\alpha + Y
  \]

• Technetium-99m (the 'm' refers to the nucleus being in a metastable state) is used in medical diagnosis as a gamma ray sources because it has a half-life of 6 hours which is a gives enough time for the measurements to be taken in hospital before the activity of the technetium decays away.
• **Wave-Particle Duality**
  • There are two aspects for Electromagnetic radiation can be regarded as a stream of 'packets' or quanta of energy, called photons (i.e. quantum aspects), traveling in straight lines. The photon is the smallest possible packet (quantum) of light; it has zero mass but a definite energy.
  • Electromagnetic radiation can also be regarded as sinusoidal varying electric and magnetic fields (i.e. wave aspects), traveling with light velocity when in vacuum. They are transverse waves: the electric and magnetic field vectors point at right angles to each other and to the direction of travel of the wave.
  • Einstein is most famous for saying "mass is related to energy". Of course, this is usually written out as an equation, rather than as words:
  
  E=m×c×c or \( E = mc^2 \)
• Because of the wave-particle duality of light, the energy of a wave can be related to the wave's frequency by the equation:

\[ E = h\nu = hf \]

• There are three measurable properties of wave motion: **amplitude, wavelength**, and frequency, the number of vibrations per second. The relation between the wavelength \( \lambda \) (Greek lambda) and frequency \( \nu \) (Greek nu) is determined by the propagation velocity \( v \);

\[ \lambda \times \nu = v \]

• This relation is true of all kinds of wave motion, including sound; although for sound the velocity is about a million times less. More usefully, since frequency is inversely proportional to wavelength, so also is photon energy:

\[ E \text{ (in keV)} = 1.24/\lambda \text{ (in nm)} \]
• For example: Blue light $\lambda=400$ nm $E=3$ eV
• Typical X- and gamma rays $\lambda=0,1$ nm $E=140$ keV
• At any point, the graph of field strength against time is a sine wave, depicted as a solid curve in Figure 1.3. The peak field strength is called the amplitude (A). The interval between successive crests of the wave is called the period (T). The frequency (V) is the number of crests passing a point in a second, and $v=1/T$. The dashed curve refers to a later instant, showing how the wave has travelled forward with velocity c.
• At any instant, the graph of field strength against distance is also a sine wave. The distance between successive crests of the wave is called the wavelength (\(\lambda\)).

• The types of radiation are listed in Table 1.2, in order of increasing photon energy, increasing frequency, and decreasing wavelength (see figure 1.3.) When the energy is less than 1 keV the radiation is usually described in terms of its frequency, except that visible light is usually described in terms of its wavelength. It is curious that only radiations at the ends of the spectrum, radio waves and X- or gamma rays, penetrate the human body sufficiently to be used in transmission imaging.
• Non-Ionizing Radiation

• Non-ionizing radiation is the radiation that has enough energy to move atoms in a molecule around or cause them to vibrate, but not enough to remove electrons. That means it does not possess enough energy to produce ions. Non-ionizing radiation consists of parts of the electromagnetic-spectrum, which includes radio waves, microwaves, infra-red, visible and ultraviolet light, together with sound and ultrasound.
• Cellular telephones, television stations, FM and AM radio, and cordless phones use non-ionizing radiation. Other forms include the earth's magnetic field, as well as magnetic field exposure from proximity to transmission lines, household wiring and electric appliances. These are defined as extremely low-frequency (ELF) waves and are not considered to pose a health risk. The electromagnetic spectrum also includes ionizing electromagnetic radiation (x and gamma rays).
• Types of Ionizing Radiation

Photon radiation can penetrate very deeply and sometimes can only be reduced in intensity by materials that are quite dense, such as lead or steel. In general, photon radiation can travel much greater distances than alpha or beta radiation, and it can penetrate bodily tissues and organs when the radiation source is outside the body. Photon radiation can also be hazardous if photon-emitting nuclear substances are taken into the body. An example of a nuclear substance that undergoes photon emission is cobalt-60, which decays to nickel-60. There are several types of ionizing radiation.
Particle Radiation

Particle radiation consists of a stream of charged or neutral particles, both charged ions and subatomic elementary particles. This includes solar wind, cosmic radiation, and neutron flux in nuclear reactors.

• Alpha Particles

Alpha particles (α), helium nuclei, are the least penetrating. Some unstable atoms emit alpha particles. Alpha particles are positively charged and made up of two protons and two neutrons from the atom's nucleus. Alpha particles come from the decay of the heaviest radioactive elements, such as uranium, radium and polonium. Even very energetic alpha particles can be stopped by a single sheet of paper. They are so heavy that they use up their energy over short distances and are unable to travel very far from the atom.
The health effect from exposure to alpha particles depends greatly on how a person is exposed. Alpha particles lack the energy to penetrate even the outer layer of skin, so exposure to the outside of the body is not a major concern. Inside the body, however, they can be very harmful.

If alpha-emitters are inhaled, swallowed, or get into the body through a cut, the alpha particles can damage sensitive living tissue. The way these large, heavy particles cause damage makes them more dangerous than other types of radiation. The ionizations they cause are very close together--they can release all their energy in a few cells. This results in more severe damage to cells and DNA.
**Beta Particles**

Beta particles (B) are fast-moving particles with a negative electrical charge. Beta particles (electrons) are emitted from an atom's nucleus during radioactive decay with more penetrating, but still can be absorbed by a few millimeters of aluminum. However, in cases where high energy beta particles are emitted shielding must be accomplished with low density materials, e.g. plastic, wood, water or acrylic glass (Plexiglas, Lucite). They travel farther in air than alpha particles, but can be stopped by a layer of clothing or by a thin layer of a substance such as aluminum. In the case of beta+ radiation (positrons), the gamma radiation from the electron-positron annihilation reaction poses additional concern. These particles are emitted by certain unstable atoms such as hydrogen-3 (tritium), carbon-14 and strontium-90.
Beta particles are more penetrating than alpha particles but are less damaging to living tissue and DNA because the ionizations they produce are more widely spaced. Some beta particles are capable of penetrating the skin and causing damage such as skin burns. However, as with alpha-emitters, beta-emitters are most hazardous when they are inhaled or swallowed.
• **Neutron Radiation**

Neutron radiation is not as readily absorbed as charged particle radiation, which makes this type highly penetrating. Neutrons are absorbed by nuclei of atoms in a nuclear reaction. This most-often creates a secondary radiation hazard, as the absorbing nuclei transmute to the next-heavier isotope, many of which are unstable. Apart from cosmic radiation, spontaneous fission is the only natural source of neutrons. A common source of neutrons is the nuclear reactor, in which the splitting of a uranium or plutonium nucleus is accompanied by the emission of neutrons. The neutrons emitted from one fission event can strike the nucleus of an adjacent atom and cause another fission event, inducing a chain reaction. The production of nuclear power is based upon this principle.
All other sources of neutrons depend on reactions where a nucleus is bombarded with a certain type of radiation (such as photon radiation or alpha radiation), and where the resulting effect on the nucleus is the emission of a neutron. Neutrons are able to penetrate tissues and organs of the human body when the radiation source is outside the body. Neutrons can also be hazardous if neutron-emitting nuclear substances are deposited inside the body. Neutron radiation is best shielded or absorbed by materials that contain hydrogen atoms, such as paraffin wax and plastics. This is because neutrons and hydrogen atoms have similar atomic weights and readily undergo collisions between each other. Figure 1.4 summarizes the types of radiation discussed in this chapter, from higher-energy ionizing radiation to lower-energy non-ionizing radiation. Each radiation source differs in its ability to penetrate various materials, such as paper, skin, wood and lead.
• **Types of Electromagnetic Ionizing Radiation**

• In general, electromagnetic radiation consists of emissions of electromagnetic waves, the properties of which depend on the wavelength. Ionizing radiation has more energy than nonionizing radiation such that it can cause chemical changes by interacting with an atom to remove tightly bound electrons from the orbit of the atom, causing the atom to become charged or ionized. The types of ionizing electromagnetic radiation are categorized according to their wavelength.
• **Gamma Rays**
• Gamma rays (γ) are weightless packets of energy called photons. Gamma-rays have the smallest wavelengths and but have much higher energy of any other wave in the electromagnetic spectrum. Unlike alpha and beta particles, which have both energy and mass, gamma rays are pure energy. Gamma rays are often emitted along with alpha or beta particles during radioactive decay and in nuclear explosions. Gamma rays are a radiation hazard for the entire body. They can easily penetrate barriers, such as skin and clothing that can stop alpha and beta particles. Gamma rays have so much penetrating power that several inches of a dense material like lead or even a few feet of concrete may be required to stop them. Gamma rays can pass completely through the human body easily; as they pass through, they can cause ionizations that damage tissue and DNA or kill living cells, a fact which medicine uses to its advantage, using gamma-rays to kill cancerous cells.
• X-Rays

• Because of their use in medicine, almost everybody has heard of x-rays. X-rays are similar to gamma rays in that they are photons of pure energy. X-rays and gamma rays have the same basic properties but come from different parts of the atom. X-rays are emitted from processes outside the nucleus, but gamma rays originate inside the nucleus. They also are generally lower in energy and, therefore, less penetrating than gamma rays but have higher energy than ultraviolet waves.
• As the wavelengths of light decrease, they increase in energy. We usually talk about X-rays in terms of their energy rather than wavelength. This is partially because X-rays have very small wavelengths. It is also because X-ray light tends to act more like a particle than a wave. X-rays can be produced naturally or artificially by machines using electricity. Literally thousands of x-ray machines are used daily in medicine. Computerized tomography, commonly known as CT or CAT scans, uses special x-ray equipment to make detailed images of bones and soft tissue in the body. Medical x-rays are the single largest source of man-made radiation exposure. X-rays are also used in industry for inspections and process controls.
• **Ultraviolet**

The dividing line between ionizing and non-ionizing radiation in the electromagnetic spectrum falls in the ultraviolet portion of the spectrum and while most UV is classified as non-ionizing radiation, the shorter wavelengths from about 150 nm (UV-C or 'Far' UV) are ionizing. UV-C from the sun is nearly all absorbed by the ozone layer.

**Bohr's proposed model of the atom**
Film Badge

This kind of dosimeter consist of two parts:

A. Photographic film.
B. The film container.

1. **Open window:** It is a large area all the radiation can pass through it, used to show the number of the film, absorbed α and β particles.
2. **Thin plastic:** This part absorbed β-particles with low energies between (0.46-0.8) MeV.
3. **Thick plastic:** This filter absorbed energies between (0.8-1.7) MeV.
4. **Duralumin:** This filter composed of mixture Al & Cu, with thickness (0.1) cm, absorbed photons with low energies between (15-65) KeV
5. **Tin & Lead:** Filter made of Tin & Lead absorbed photons with energies between (75 KeV-2 MeV).
6. **Cad & Lead:** This filter made of Cad & Lead absorbed the slow photons.
Biological effect of Radio active
The effects of radiation on the human body result from damage to the individual cells. These effects may be divided into two classes.

- **The somatic effects:**
  Which arise from damage to the ordinary cells of the body and affect only the irradiated person.

- **The genetic effect:**
  Which are due to damage to the cells in the reproductive organs, the gonads, in this case the damage may be passed on to the person's children and subsequently to a later generation.
1. The somatic effect of radiation

A. Acute radiation exposure (exposure received in relatively short time).

Since not all organs are equally sensitive to radiation, the pattern response or syndrome.

In an over exposed person depends on the magnitude of the dose the acute radiation syndrome is subdivided in to three classes.

➢ The hemophiliac syndrome.
➢ The gastrointestinal syndrome.
➢ Central nervous system syndrome.

One of the most common effects of acute radiation is blood changes usually blood changes appear at doses of 25 – 50 R (Roentgen)
Composition of Blood

- White blood cells (Leukocytes)
  - (Granulocytes 70 – 75%)
  - (Lymphocytes 25 – 30%)
- Red blood cells (erythrocytes)
- Platelets (thrombocytes)
- Plasma

A total body exposure to acute dose of radiation between 0 – 25 R dose not show any effect.
The granulocytes are produced in the bone marrow.
The lymphocytes are produced in lymph nodes.
The red blood cells are produced also in the bone marrow.
The platelets also are produced in the bone marrow.

White blood cells respond more rapidly to radiation than red blood cells after some time of acute exposure. The number of white blood cells will reduce (leukopenia), also at later time the number of red blood cells will decrease (anemia).
They may return to normal count after a period of several weeks to several months.

The blood count changes depend on the radiation dose but should not be used as a mean of Radiation monitoring though they are the most sensitive biological indicators.
The symptoms of the tissue forming blood

- **Hemopoietic syndrome**: This appears after an exposure dose of about 200R.
  - Depression of the bone marrow and the consequences of this damage
  - Nause and vomiting
  - Malaise and fatigue
  - Death may occur
- **Gastrointestinal syndrome**: This appears after a total body exposure of about 1000 R as a consequence of the peeling of the intestinal epithelium.
  - In addition to that all the symptoms of hemopoietic syndrome are seen but more severe.
  - Death is most likely to occur within one to two weeks after exposure.
Central nervous system syndrome:

- A total body exposure of about 2000R or more damages the nervous system. Unconsciousness follows within minutes after exposure. Death occurs within hours to several days.
Other a cute effects:

- **Skin effects**, such as erythema which is caused by exposure of about 300R, of low energy X-rays. At higher doses ulceration will be produced.

- **The gonads** are radio sensitive temporary sterility in both man and woman may be caused by a single exposure of 30R to the gonads in man and 300R in woman. Higher doses increased the period of temporary sterility.
These effects are due to continuing low levels doses of radiation received over a long period of time (Chronic exposure) these effects are:

- **Cataract formation:**
  - Which appears to have a threshold $\gamma$-dose of about 500 Rad fast neutrons are more effective.

- **Induction of cancer:**
  - Leukemia (Cancer of white blood bone marrow)
  - Bone cancer
  - Thyroid cancer
  - Lung cancer

- **Life shortening:**
  - Radiation shorten the life span by increasing the rate of physiological aging.
2) the genetic effects of radiation:

- The genetic effects of radiation result from damage to the reproductive cells. This damage takes the form of alteration. Known as genetic mutation in the hereditary material of the cell (genes & chromosomes) heat and chemicals can also cause mutation, normally if a mutant gene mates with an undamaged gene of the same type, the damage will not become evident in the offspring because radiation mutations are usually recessive if by chance two genes of a mating pair are both damaged the damage will affect the offspring.
- Therefore the radiation will increase the number of genetically abnormal people. Present in the future generations.
• **Exposure X:**
• **The exposure** is the absolute value of the total charge of the ions produced in air when all the electrons liberated by photons per unit mass of air are completely stopped in air.
• \( X = \Delta Q/Am \)
• \( \Delta Q \): is the sum of electric charges of all the ions produced in air when all the electrons liberated by photons in a volume of air.
• \( \Delta m \): is the mass of the volume of air under consideration.
• In honor of the discoverer of x rays, the unit of exposure is the Röntgen defined
• as:
  \[ R \text{ Röntgen} = 2.58 \times 10^{-4} \text{Cb/kg} \]
• which is equivalent to the production of 1 electrostatic unit (esu) of charge of one sign from the interaction of x rays or gamma rays in 0.001293 grams of air at standard temperature and pressure (STP) which is equivalent to 1 cm\(^3\) of air at atmospheric pressure and 0 degrees Celsius, where:
• 1 esu = 3.33 \times 10^{-10} \ [\text{Cb}]
• For a smaller magnitude, the milliRöntgen is defined as:
• 1 mR = 10\(^{-3}\) R
• The exposure rate is defined as:
• \( x = \frac{dx}{dt} \left[ \frac{r}{\text{sec}} \right] \) or \( \left[ \frac{mR}{hr} \right] \)
• It must be noticed that the concepts of exposure and exposure rates apply only to x rays and gamma rays not to other forms of radiation such as neutrons or charged particles, and that they are defined only in air and not in inert or biological materials.
• there are two potential primary exposure types: external and internal exposure to radiation.
• The external dose: is that portion of the dose equivalent received from radiation sources outside the body. This is primarily a concern for gamma & X-ray radiation.
• The internal dose: is that portion of the dose equivalent received from radioactive materials inside the body. The internal dose is directly related to the intake of radioactive materials.
• It Intake is the quantity of material introduced into the body by inhalation, ingestion or through the skin (absorption, puncture, etc.).
• Depending on the radionuclide, the dose can be localized to specific organs, or distributed across the whole body.
• An acute exposure: is the absorption of a relatively large amount of radiation (or intake of radioactive material) over a short period of time.
• A chronic exposure: is the absorption of radiation (or intake of radioactive materials) over a long period of time, i.e., over a lifetime.
• A radiological dose assessment calculates the amount of radiation energy that might be absorbed by a potentially exposed individual as a result of a specific exposure.
• **Absorbed Dose (D):**
  • In simple term is the energy imparted by ionizing radiation to unit mass of matter. The unit of absorbed dose is **gray (Gy)** & rad.

• Absorbed dose: 
  \[ D = \frac{\text{imparted energy}}{\text{Mass}} = \frac{\Delta E_D}{\Delta m} \]

• A unit for the absorbed dose in the conventional system of units is the Rad standing for Radiation Absorbed Dose as:
  • \( 1 \text{ Rad} = 0.01 \left[ \frac{\text{Joule}}{\text{kg}} \right] = 100 \left[ \frac{\text{ergs}}{\text{gm}} \right] \)

• In the Système International (SI) system of units, the unit for the absorbed dose is:
  • \( 1 \text{ Gray} = 1 \text{ Gy} = 1 \left[ \frac{\text{joule}}{\text{kg}} \right] = 100 \text{ rads} \)
  • -1 Gy = 100 rad
  • -1 gray (Gy) = 1 J/kg
• **Radiation Weighting Factors** ($W_R$):

• It is recognized that different types of ionizing radiations will have different degree of harmless to human body even the absorbed dose is the same. Radiation weighting factors are used to account for the difference. For example, neutrons are more damaging than X-ray and so a factor of 20 is given to neutrons. The radiation weighting factor for X-ray is 1.
• **Equivalent Dose** ($H_T$):

  Is a measure of the biological damage to living tissue resulting from exposure, in other words, is a weighted dose in an organ or tissue. It is determined by the product of average absorbed dose in an organ or tissue with the radiation weighting factor ($WR$). The unit of equivalent dose is sievert ($Sv$).

  $$H_T = \sum W_R D$$

  $W_R$: radiation weighting factor for radiation R.

  $D$: absorbed dose averaged over the organ or tissue $T$.

  Expressed in units of rem or Sievert ($Sv$) ($1 \text{ Sv} = 100 \text{ rems}$)

  $1 \text{ mrem} = 0.001 \text{ rem}; 1 \text{ mSv} = 0.001 \text{ Sv}$
• **Tissue Weighting Factors** \((W_T)\):

The probability of occurrence of some radiation effects in an organ or tissue is assumed to be proportional to the equivalent dose in the organ or tissue for radiation protection purposes. The effects of radiation may differ for various tissues of the body.

Tissue weighting factors are therefore introduced to represent the proportion of the risk resulting from irradiation of an organ or tissue of the body to the total risk when the whole body is irradiated.
• **Effective Dose (E);**

The effective dose, $E$, a measure of the whole body dose by the summation of the weighted equivalent factors doses in all the tissues and organs of the body. It represents the total risks to the whole body due to partial irradiation of body organs. It is given by the expression

$$ E = \sum H_T W_T $$

• $H_T$: is the equivalent dose in organ or tissue $T$.
• $W_T$: is the weighting factor for that organ or tissue.
Radiation Dose vs Radiation Exposure: -

Radiation exposure is related to the amount of ionization of air produced by an x-ray beam. It is a radiation source-related term and is a measured quantity.

Radiation dose is a body-related term and is calculated from the exposure. For a given measure of radiation exposure, we can specify the amount of radiation energy deposited in the patient's body as a result of that exposure.
• **Factors Affecting Radiation Dose**

Radiation dose must be optimized. Insufficient radiation dose results in increased noise and degradation of image quality. An increase in radiation dose above a certain level does not further improve image quality; it merely deposits more radiation in the patient's body. Radiation dose can be modified by adjusting the tube voltage, tube current, scan time, scan coverage, collimation or detector configuration, pitch, and table movement.
Dose Affecting Factors in radiography:

- **X-RAY BEAM ENERGY (KVP):** The amount of tube voltage (kVp) affects radiation dose. Reduction of the tube voltage will decrease the output of the x-ray tube and reduce the radiation dose to the patient.

- **TUBE CURRENT AND EXPOSURE TIME (mA):** The patient dose is proportional to mAs.

- **ADDED FILTRATION:** Higher added filtration results in lower dose.

- **COLLIMATION:** Aggressive collimation reduces the irradiated area as well as scatter radiation.

- **GRIDS:** Grids reduce scatter radiation but increase patient dose.

- **IMAGE RECEPTOR:** Faster speed image receptor reduces patient dose.

- **PATIENT SIZE**
• **Dose Affecting Factors in Mammography:**
  • Filter materials: filter target combination.
  • Grids
  • Mag mode: magnification increases dose.
  • Compression
  • Breast size and tissue composition
**Dose Affecting Factors in CT scan:**

- **kVp tube**
- Routine body CT for adult patients is generally performed at 120 to 140 kVp.
- The use of 80 kVp is a well-accepted level when attempting to reduce radiation doses in pediatric patients.
- **tube current & time (a mAs).**
- Pitch and radiation dose: overall radiation dose and scan duration decrease proportionally with increasing pitch (or table speed).
- **patient size.**
- size of patient imaged.
• **Dose Affecting Factors in NM medicine:**
  • biology
  • uptake and clearance rates of activity in various source organs.
  • patient geometry (organ size and orientation).
  • radioactive decay characteristics
  • half-life
  • number, type & energy of emissions.
Human responses to ionizing radiation

- the following outline summarizes the possible early and late human responses to radiation exposure:

  - early effect of radiation on humans:
    - 1. Acute radiation syndrome
      - a. hematologic syndrome
      - b. gastrointestinal syndrome
      - C. central nervous system syndrome
    - 2. Local tissue damage
      - a. skin
      - b. Gonads
      - c. Extremities
    - 3. Hematological depression
    - 4. Cytogenetic damage

- Late effects of radiation on humans
  - 1. Leukemia
  - 2. other malignant disease
    - a. bone cancer
    - b. Lung cancer
    - c. Thyroid cancer
    - d. Breast cancer
• Local tissue damage
  • a. skin
  • b. Gonads
  • C. Eyes
• 4. Life span shortening
• 5. Genetic damage
• C. Effects of fetal irradiation
  • 1. Prenatal death
  • 2. Neonatal death
  • 3. Congenital malformation
  • 4. Childhood malignancy
  • 5. Diminished growth and development
Physical factors affecting radiosensitivity:

• when one irradiates a biologic medium, the response of the medium will be determined by the amount of energy deposited per unit mass. Even under controlled experimental conditions, when equal doses are delivered to equal specimens, the response may not be the same because of other modifying factors.

• there are a number of physical factors that affect the degree of radiation responses:
• 1. Linear Energy Transfer (LET):

- The (LET) is a measure of the rate at which energy is transferred from ionizing radiation to soft tissue. It has units of Kev of energy transferred per micrometer of track length in soft tissue (Kev/um). The ability of ionizing radiation to produce biological response increases as the LET of radiation increases. The following table shows the approximate LET of various types of radiation.
<table>
<thead>
<tr>
<th>Type of radiation</th>
<th>LET (KeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 MV X-rays</td>
<td>0.2</td>
</tr>
<tr>
<td>Co rays</td>
<td>0.25</td>
</tr>
<tr>
<td>1 MeV electrons</td>
<td>0.3</td>
</tr>
<tr>
<td>Diagnostic x-rays</td>
<td>3</td>
</tr>
<tr>
<td>10 MeV protons</td>
<td>4</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>50</td>
</tr>
<tr>
<td>5 MeV alpha particles</td>
<td>100</td>
</tr>
<tr>
<td>Heavy nuclides</td>
<td>1000</td>
</tr>
</tbody>
</table>
- **Relative biological effectiveness:**

- as the LET of radiation increase, the ability to produce biologic damage also increases. This relative effect is quantitatively described by the relative biologic effectiveness (RBE).

- **the RBE is defined as follows:**

\[
\text{RBE} = \frac{\text{dose of standard radiation necessary to produce a given effect}}{\text{dose of test radiation necessary to produce the same effect}}
\]

- diagnostic x-rays have an RBE of 1. radiation with lower LET than diagnostic X-rays have an RBE less than 1, whereas radiation with higher LET have a higher RBE
Example: when mice are irradiated with 250 KVP X-rays, 640 rad (6.4 Gy) are necessary to produce death. If similar mice are irradiated with fast neutrons, only 210 rad (2.1 Gy) are needed. What is the RBE for the fast neutrons?
• **Fractionation and Protraction:**
  • If a dose of radiation is delivered over a long period of time rather than quickly, the effect of that dose will be less. This lengthening of time can be accomplished in two ways.
  • If the dose is delivered continuously but at a lower dose rate, it is said to be **protracted**. Such as, 600 rad delivered in 3 min is lethal for a mouse. When 600 rad is delivered at the rate of 1 rad/hr for a total time of 600 hr, the mouse will survive.
  • Dose protraction is less effective because of the lower dose rate and the longer irradiation time.
  • If the 600 rad dose is delivered at the same dose rate 200 rad/min, but in 12 equal fractions of 50 rad, each separated by 24 hr, the mouse will be survive. In this situation the dose is said to be fractionated dose fractionation is less effective because tissue repair and recovery occur between doses. Dose fractionation is employed routinely in radiation oncology.
• Biological factors affecting radiosensitivity:
  • Oxygen effect
  • biological tissue is more sensitive to radiation when irradiated in the oxygenated, or of aerobic state than when irradiated under anoxic (without oxygen) or hypoxic (low oxygen) conditions.
  • this characteristic of biologic tissue described numerically by the oxygen enhancement ratio (OER). ratio (OER).
  • \( OER = \frac{\text{dose necessary, under anoxic conditions to produce a given effect}}{\text{dose necessary under aerobic conditions to produce the same effect}} \)

• Hyperbaric (high pressure) oxygen has been used in radiation therapy in attempt to increase the radio sensitivity of nodular, vascular tumors, which are less radio sensitivity than tumors in other parts of body.
• Example: when experimental mouse are irradiated under hypoxic condition, the tumor control dose is 10600 rad. When the tumors are irradiated under aerobic conditions by 4050 rad. What is the OER for the system?

• Age:

• The age of a biologic structure affects its radio sensitivity. Humans are most sensitive before birth, the sensitivity then decreases until maturity. In old age humans again become somewhat more radiosensitive.
• **Recovery:**

• Human cells are capable of recovering from radiation damage. If the radiation dose is not sufficient to kill the cell before its next division (interphase death), then given sufficient time the cell will recover from the sub-lethal radiation damage it sustained.

• At the whole body level this recovery from radiation damage is assisted through repopulation by the surviving cells. If a tissue or organ receives a sufficient radiation dose, it will respond by shrinking in size. This is called atrophy and occurs because some cells die, disintegrate, and are carried away as waste products. If a sufficient number of cells sustain only sub-lethal damage and survive, they may proliferate and repopulate the irradiated tissue or organ. The combined processes of repair and repopulation contribute to recovery from radiation damage.
• **Chemical agents:**
  some chemicals can modify the response of cells, tissue, and organs to radiation. For the chemical agents to be effective, they generally must be present at the time of irradiation post irradiation will not usually alter the degree of response.

• **Radio sensitzers:**
  Agent that enhance the effect of radiation are called sensitizing agents. Some examples are halogenated pyrimidines, methotrexate, actinomycin and vitamin K. The halogenated pyrimidines become incorporated into the DNA of the cell and cause the radiation effects on that molecule to be amplified.

• **Radioprotectors:**
  The radioprotective compound include molecules a sulfhydryl group (sulfer and hydrogen bound together) such as cysteine and cysteamine. For example, if 500 rad is a lethal dose to a mouse then in the presence of a radio protective agent 1000 rad would be required to produce lethality.
<table>
<thead>
<tr>
<th>Quantity</th>
<th>Old unit</th>
<th>SI unit</th>
<th>Relation between unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radioactivity</td>
<td>Curie (Ce)</td>
<td>Becquerel (Bq)</td>
<td>1 Bq = $2.7 \times 10^{-11}$ Curie, 1 Ci = 37 giga Bq.</td>
</tr>
<tr>
<td></td>
<td>Curie = $3.7 \times 10^{10}$ dis/sec</td>
<td>Bq = 1 dis/sec</td>
<td></td>
</tr>
<tr>
<td>Exposure</td>
<td>Roentgen</td>
<td>Air Kerma</td>
<td>1 Gray = 114.5 Roentgen, 1 Roentgen = 8.73 m Gray</td>
</tr>
<tr>
<td>Absorped Dose</td>
<td>Rad</td>
<td>Gray</td>
<td>1 Gray = 100 Rad, 1 Rad = 0.01 Grey</td>
</tr>
<tr>
<td></td>
<td>1 Rad = 0.01 Joul/Kg</td>
<td>1 Gray = 1 Joul/kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>= 100 erg/gm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dose equivalent</td>
<td>Rem</td>
<td>Sievert (sv)</td>
<td>1 Sv = 100 Rem, 1 Rem = 10 m Sv</td>
</tr>
</tbody>
</table>

1 ev = $1.6 \times 10^{-12}$ erg
= $1.6 \times 10^{-19}$ Joul

1 Roentgen = $2.58 \times 10^{-4}$ coul/kg.

1 curie = $3.7 \times 10^{10}$ dis/sec.
Radiation Protection

- **Rad**: is depended as an energy deposited of \((0.01 \text{ J/Kg})\) in any medium by all types of radiation or \(1 \text{ Rad} = 100 \text{ erg/gm}\).

- **Curie**: is defined as the activity of that quantity of radiation material in which the number the disintegration per second is \((3.7 \times 10^{10})\), \(1 \text{ Curie} = 3.7 \times 10^{10} \text{ dis/sec}\).

- **Roentgen**: which corresponds to the production of ions (of one sign) carrying change of \((2.58 \times 10^{-4} \text{ Coul/Kgm of air})\).

- **Rem**: The amount produced by multiplying absorbed dose and quality factor.

- **Equivalent Dose (H_T)**:

  \[
  \text{Equ. dose} = \text{Absorbed dose} \times \text{Quality factor}
  \]

- **Quality factor (Q.f)**:

  When different radiation have to be added we must multiply the absorbed dose (in rad) of each type radiation by Quality factor.
The value of \((Q.f)\) depend on the density of Ionization caused by radiation.

**Q :** The dose rate outside the shielding of cyclotron is found to be:

- \(0.5\) m rad / hr ....... \(\gamma\) – radiation.
- \(0.2\) m rad / hr ....... thermal neutrons.
- \(0.1\) m rad / hr ....... fast neutrons.

**Answer :** From the table above we take the \(Q.f\).

Now \(\text{equ. Dose} = \text{absorbed dose} \times Q.f\)

- \(\text{equ. Dose} = 0.5 \times 1 = 0.5\) mRem for \(\gamma\) – radiation.
- \(\text{equ. Dose} = 0.2 \times 3 = 0.6\) mRem for thermal n°.
- \(\text{equ. Dose} = 0.1 \times 10 = 1\) mRem for Fast n°.

\[\therefore \text{total equ. Dose} = 0.5 + 0.6 + 1 = 2.1\] mRem / hr.