Radiation Physics

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Lecture 1

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Matter and Energy

Physics is a science dealing with nature. It is concerned with the study of two concepts, matter and energy, and how they interact with each other. Matter is one, which occupies space, and it is made up of molecules or atoms, e.g. gold, wood, water and air. Matter exists in solid, liquid, gas, liquid crystal, and plasma state. Matter can be converted from one form to another by physical or chemical means, e.g. melted ice converts from solid to liquid form by physical process and burning of wood into ash is a chemical process. The Energy of a body is its ability to do work. It is measured by the amount of work that it can perform. The SI unit of energy is joule. The electron volt (eV) is also used as unit of energy in radiation physics. There are many forms of energy, such as mechanical energy, heat energy, light energy, electrical energy, chemical energy, etc. There are two forms of mechanical energy, potential energy and kinetic energy.

Mass Energy Equivalence

Einstein’s theory of relativity states that mass and energy are equivalent and are interchangeable. In any reaction, the sum of the mass and energy must be conserved. Einstein showed that the speed of some nuclear processes approach the speed of light. At these speeds, mass and energy are equivalent.

$$E = mc^2$$

where, E represents the energy equivalent to mass ‘m’ at rest and ‘c’ is the speed of light in a vacuum. For example, the energy equivalent of an electron of mass 9.109×10^{-31} kg is

$$E = mc^2 = 9.109 \times 10^{-31}\ \text{kg} \times (2.998 \times 10^{8}\ \text{m/s})^2 = 0.511\ \text{MeV}$$

The Atom

Atoms are far too small to see directly, even with the most powerful optical microscopes. All matter is composed of atoms. A sample of a pure element is composed of a single type of atom. Chemical compounds are composed of more than one type of atom. Atoms themselves are complicated entities with a great deal of internal structure. An atom is the smallest unit of matter that retains the chemical properties of a material.

Structure of The Atom

An atom consists mainly of empty space. The basic structure of an atom is a positively charged nucleus, containing electrically neutral neutrons and positively charged protons, surrounded by one or more negatively charged electrons as shown in figure 1.

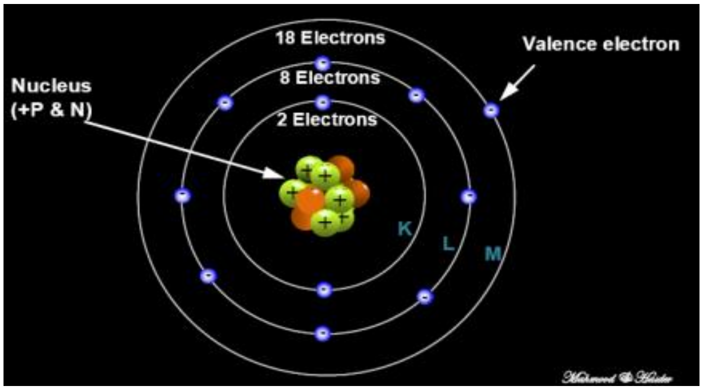


Figure 1: Atomic structure a sodium atom.

- The nucleus consists of two particles called protons and neutrons and collectively known as nucleons. The protons are positively charged and the neutron has no charge. The protons has a charge of 1.6×10^{-19} coulombs (C) Protons and neutrons have approximately the same mass, about 1.67×10^{-24}. grams.
- The electrons are negative charges, each electron has energy which enables it to resist the positive charge of the nucleus. An atom is electrically neutral if the total electron charge equals the total proton charge. Electrons are bound to the positively charged nucleus by electrostatic attraction. The number and distribution of electrons in the atom determines the chemical properties of the atom. An electron carries the same numerical charge as the proton, but of opposite sign Electrons are much smaller in mass than protons, weighing only 9.11×10^{-28} grams, or about 1/1800 of an atomic mass unit. Therefore, they do not contribute much to an element's overall atomic mass. When considering atomic mass, it is customary to ignore the mass of any electrons and calculate the atom's mass based on the number of protons and neutrons alone.

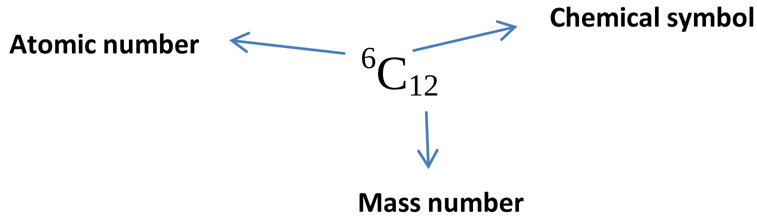
Atomic Number and Mass Number

Atomic number, it is also equal to the number of electrons of the atom, which is represented by Z.

The mass number of an atom is the total number of protons and neutrons (N) in the nucleus and it is denoted by A.

$$N=A-Z$$

An element (X) is symbolically described as $^{Z}X_{A}$. The subscript gives the atomic number Z while superscript gives the mass number A.



Neutral atoms of an element contain an equal number of protons and electrons. **Atomic mass** is the average mass of an atom, taking into account all its naturally occurring isotopes.

Isotopes

The atoms composed of nuclei with the same number of protons but different number of neutrons is called isotopes. In other words, isotopes have the same atomic numbers and different mass numbers, e.g. hydrogen have 3 isotopes, namely:

$_{1}H^{1}$ have 1 proton (Hydrogen),

$_{1}H^{2}$ have 1 proton and 1 neutron (Deuterium)

$_{1}H^{3}$ have 1 proton and 2 neutrons (Tritium).

Isotopes of an element have the same chemical properties but have different physical properties. Isotopes capable of performing radioactivity are called radio-isotopes and their nucleus is said to be unstable.

ELECTRON SHELLS

Electrons are most likely to be at fairly well-defined distances from the nucleus and are described as being in 'shells' around the nucleus (Figure 1). More important than the distance of the electron from the nucleus is the electrostatic force that binds the electron to the nucleus, or the amount of energy the electron would have to be given to escape from the field of the nucleus. This is equal to the amount of energy a free electron will lose when it is captured by the electrostatic field of a nucleus. The maximum number of electrons in each shell can be obtained from the formula $2n^2$ where *n* is the shell number, n = 1, 2, 3, 4, etc. In the case of K shell, n = 1, the number of electrons in the K shell = $2 \times 1^2 = 2$. In the case of L shell, n = 2, the number of electrons in the L shell = 2 × 22 = 8 and so on. Each shell is provided with subshells, which are denoted as s, p, d, f, etc. The K shell (n = 1) has one subshell, namely, 1s. The L-shell (n = 2), has two subshells, namely, 2s and 2p and so on. In each atom, the outermost or valence shell is concerned with the chemical, thermal, optical and electrical properties of the element. X-rays involve the inner shells, and radioactivity concerns the nucleus.

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.

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 binding energy of an electron (E_b), also called *ionization potential (IP)*, is the energy required to remove an electron from an atom, a molecule, or an ionis defined as the energy required to completely separate the electron from the atom.

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 ($\mathbf{E}_K > \mathbf{E}_L > \mathbf{E}_M \cdots$), 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. For example, to move an electron from K to L shell of the hydrogen atom, the energy required is (–3.4 eV) – (–13.5 eV) = 10.1 eV.

Ionization and Excitation

Removal of one or more electrons from a neutral atom is called ionization. After ionization, the remainder of the atom is left with positive charge and is known as positive ion. The positive atom and the removed electrons form one ion pair.

In an atom, if energy is supplied, the electrons can be moved from the inner orbit to the outer orbit. Now, the atom will have more energy than its normal state. It is said to be in an excited state and the process is known as excitation. For example, to move an electron from K to L shell of the hydrogen atom, the energy required is (–3.4 eV) – (–13.5 eV) = 10.1 eV.

SI Units

In 1960, a new system of units called Systems International units (SI Units) was introduced. The SI system is superior to all other systems and more convenient in practice and is used throughout the world. There are 7 fundamental units and 2 supplementary units in the SI system as shown in the Table 1.

Table 1: SI system of units

Physical quantity	Unit	Symbol
Length	Meter	M
Mass	kilogram	Kg
Time	Second	S
Electric	Ampere	A
Temperature	Kelvin	K
Luminous intensity	Candela	Cd
Amount of substance	Mole	Mol
Plane angle	Radian	Rad
Solid angle	Steradian	Sr

Prefixes

Though the SI units are a coherent system, they are found to be either too large or low in practice, e.g. the activity of an isotope for bone scan is expressed in billions of becquerel's. Hence, prefixes are used to overcome the above difficulty, as shown in Table 2. These prefixes are conveniently used to describe very large or small physical quantities. In radiation physics, giga becquerel (GBq), kilovolt (kV), centi gray (cGy), milli ampere (mA), and nanometer (nm) are commonly used.

Table 2: Prefixes used with SI units

Prefix	**Symbol**	**Factor**	
tera	T	10^{12}	
giga	G	10^{9}	
mega	M	10^{6}	1Mm=10^{6} m
kilo	k	10^{3}	1km=10^{3} m
deci	d	10^{-1}	
centi	c	10^{-2}	
milli	m	10^{-3}	1mA=1×10^{-3} A
micro	μ	10^{-6}	1μC=1×10^{-6} C
nano	n	10^{-9}	ns=10^{-9} n
pico	P	10^{-12}	1PC=1×10^{-12} C
femto	f	10^{-15}	1fm=1×10^{-15} m