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Oral & Maxillofacial RADIOLOGY

Basic Principles and Interpretation



Foreword
Yeshwant B Rawal

Kamala G Pillai

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CHAPTER 2

Nature and Characteristics of Radiation

CHAPTER OUTLINE

- Structure of an Atom
- Nucleus
- Electrons
- Ionization
- Isotopes
- Particulate Radiation
- Protons
- Neutrons

Physics is a science concerned with the study of two concepts, matter and energy, and how they interact with each other. Radiation physics is the study of that aspect of physics pertaining to the origin, nature and behavior of X-rays and other related types of radiations.

Universe is made up of matter, which can be solid, liquid or gas that is divided into elements and compounds. It has a mass and can exert force or be acted on by a force. Matter can neither be created nor destroyed and can be easily converted into other forms. The building block unit of matter is called atoms. Atom is the smallest particle of an element that has characteristic properties of that element. This cannot be subdivided by ordinary chemical methods, but may be broken down into subatomic particles by special high-energy techniques. These subatomic particles, namely electrons, protons and neutrons are of special significance since the generation, emission and absorption of radiation occurs at the subatomic level.

Energy is a concept, which is difficult to define concisely, but it is easy to understand. Energy can be defined as the ability to do work or as the actual or potential ability to do work. There are different forms of energy namely mechanical, chemical, thermal, electrical, light, X-rays, etc. As in the case of matter, energy can neither be created nor destroyed and all forms of energy can be converted more or less easily into other forms. Energy exists in several different forms and this is used for different purposes. Any form of energy can be converted into another form or forms without loss to the total energy in the system. Energy of a moving body is called kinetic energy. A body may also have potential energy. Potential energy is the energy possessed by a body or system by virtue of its condition or state.

STRUCTURE OF AN ATOM

To understand the nature and the effects of natural or manufactured radiation energy, knowledge of the structure of an atom is essential. An atom is defined as the smallest particle of an element that can exist without losing the chemical properties of the element. An atom is composed of a central nucleus consisting of protons and neutrons. Protons are positively charged and neutrons have no charge. Atom also consists of a number of lighter particles with negative charge called electrons, which rotate around the nucleus in definite orbits (orbiting electrons, **Figs 2.1 and 2.2**). The physical and chemical properties of an atom are determined by the composition of its nucleus and the arrangement of its orbiting electrons respectively. The atom is said to be electrically neutral when the number of positive charges of the nucleus (protons) equals the negative charges of the orbital electrons. Different materials like gold, lead and aluminum will have different number of protons/electrons in their atoms. However, all the atoms in a given material will have the same number of electrons and protons. The electrons are maintained in their orbits around the nucleus by two opposing forces. The first of these known as the electrostatic force, is the attraction

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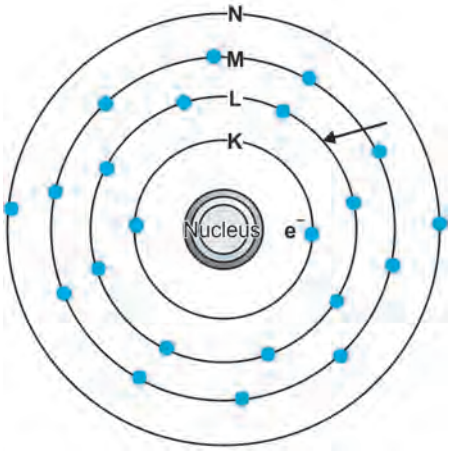

FIG. 2.1 Structure of an atom, shows nucleus, electrons and orbital shells (left arrow)

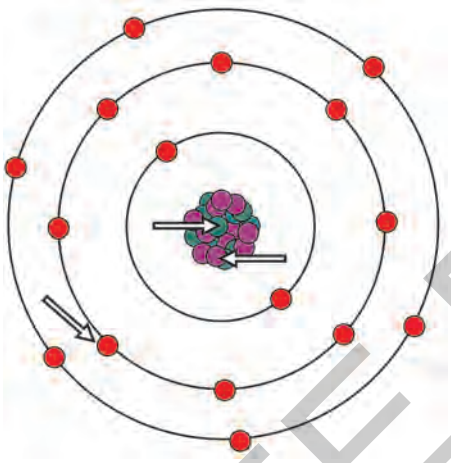

FIG. 2.2 Shows protons (right arrow), neutrons (left arrow) and electrons (oblique arrow)

between negative electrons and the positive protons. This attraction causes the electrons to be pulled toward the protons in the nucleus. In order to keep the electrons from dropping into the nucleus, the other force, known as centrifugal force pulls the electrons away. The balance between the electrostatic attraction of unlike charges and the centrifugal forces of the fast moving electrons keeps the electrons in the orbit around the nucleus.

NUCLEUS

Nucleus is the positively charged central core of the atom. The nuclear diameter is about 10^{-15} m and is surrounded by an extranuclear space, which is occupied by the electrons of the atom. The nucleus or the dense core of the atom is composed of particles known as protons (positively charged subatomic particles) and neutrons (subatomic particles with no charge). Protons and neutrons are known as nucleons (particles present in the atomic nucleus). The number of protons contained in the nucleus determines the positive charge of the atom. Protons carry a positive electrical charge, which is equal in size, but opposite in sign to the charge carried by the electrons. The neutrons carry no electrical charge and are similar in size and mass to a proton. Atoms differ from one another based on their nuclear composition. The number of protons and neutrons in the nucleus of an atom determines its mass number or atomic weight, which is designated by the symbol (A). The number of protons inside the nucleus equals the number of electrons outside the nucleus in a neutral atom and determines the atomic number (Z) of the atom. The chemical properties of an atom are determined by the atomic number. Since the atom in the ground state is electrically neutral, the total number of protons and electrons must be the same.

The nucleus must be visualized as a dynamic rather than a static structure where there are opposing forces acting. Some forces tend to hold the nucleus together and some tend to disrupt it. If the forces acting to disrupt the nucleus overcome those holding it together, the nucleus is said to be unstable and this nucleus is said to undergo radioactive decay. Forces which hold the nucleus together are short-range nuclear forces. They act over distances of about 10^{-15} m, over which range they are much more powerful than the electrostatic forces between protons. Neutrons also act as a binding agent to hold the protons together. The energy expended in keeping the nucleus together is known as the nuclear binding energy. The binding energy per nucleon is obtained when nuclear binding energy is divided by the number of nucleons in the nucleus and is about 8.4 MeV (mega electron volts) for most nuclei.

A concept of nuclear shells has been suggested where there is a layering within the nucleus with maximum stability being produced when a shell is complete. The atom remains stable and neutral until some force such as electromagnetic energy can cause an imbalance in the structure.

ELECTRONS

Electrons are very small negatively charged particles (carry 1 unit of negative electric charge) that have very little mass and are found in the extranuclear space of the atom. Electrons travel around the nucleus in well-defined paths known as orbits or shells. The electron orbits or shells can be represented two-dimensionally as circles, but

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atoms however, are three-dimensional and the shells are ellipsoidal. Electrons associate themselves with various energy levels around the nucleus of the atom. Any electron has a finite probability of being anywhere in space but their most probable position lies near the orbits that correspond to the discrete measurable energy levels of the atom. The shells lie at defined distances from the nucleus. An atom has a maximum of seven shells (no known atom contains more than seven shells), each located in a specific distance from the nucleus representing different energy levels. The arrangement of the electrons around the nucleus determines the way atoms interact with each other. Each shell has a maximum number of electrons it can hold, having approximately the same energy in each shell or orbits **(Fig. 2.3)**. A letter or number (principal quantum number) identifies them. Innermost shell is known as K shell or one, next as L or two and remaining as M, N, O, P and Q **(Fig. 2.4)**. Only two electrons may occupy the K shell with increasingly large number of electrons occupying the outer shells. Each orbit/shell is allowed to contain a maximum number of electrons. The maximum number of electrons in an orbit is equal to $2n^2$ where n is the principal quantum number of the shell (e.g. n = 1 = K shell, n = 2 = L shell, etc.). Thus, if the principal quantum number of the shell is 2, then the maximum number of electrons that can occupy the shell is 8 and if it is 3, then the maximum number of electrons that can occupy that shell are 18 and so on. Electrons in the outermost shell are termed valence electrons, which determine the chemical properties of an atom. Maximum number of electrons that can exist in each shell is:

K shell = 2, L shell = 8, M shell = 18, N shell = 32, O shell = 50, P shell = 72, Q shell = 98.

The orbits/shells of an atom are represented diagrammatically in two ways. Firstly, a circular orbital/shell diagram **(Fig. 2.4)** or an energy level diagram **(Fig. 2.5)**.

The energy level diagram shows different binding energies and energy levels of each shell. With regards to **(Fig. 2.5)**, the energy emitted as an electron moves from n = 1 to n = 4 is greater than the energy emitted if an electron moves from n = 1 to n = 2 since the difference in binding energies is less.

In the normal atom, there is a balance between centrifugal force and electrostatic force. This balance between the forces will result in a definite electron path or orbits for each electron around the nucleus of an atom. Electrons are maintained in their orbits by the electrostatic force, or attraction between the positive nucleus and the negative electrons. Higher the atomic number of an atom (more protons), higher the electrostatic force will be for all electrons in that atom.

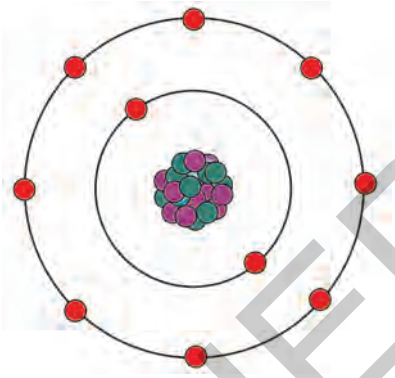

FIG. 2.3 Shows maximum number of electrons that can exist in each orbital shell (only in K and L shell represented)

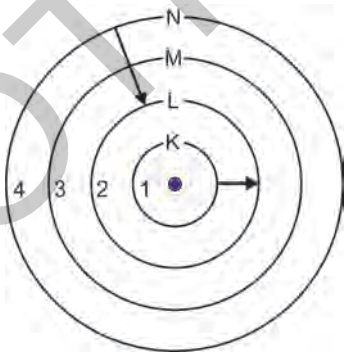

FIG. 2.4 Shows shells in an atom

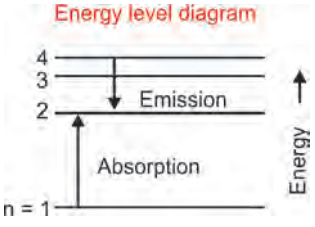

FIG. 2.5 Orbital energy levels

Electrons in the orbit closest to the nucleus, e.g. K shell will have a greater electrostatic force than will electrons in orbits farther from the nucleus. Another term often used is binding energy. This basically represents the amount of energy required to overcome electrostatic force to remove an electron from its orbit. For our purposes, electrostatic force and binding energy are the same. This is the binding force of an electron and is specific for each shell of each atom. Each shell has a different energy level, which is dependent on the atomic number of the atom and the distance the electron is from the nucleus. The energy required to remove an electron from a particular shell is designated as binding energy of that shell. The binding energy is determined by the distance between the nucleus and the

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orbiting electron and is different for each shell. The binding energy is largest for the K shell, because of its proximity to the positively charged nucleus and decreases progressively for successive shells. However, farther away the electron is situated from the nucleus, the greater the potential energy. The electrostatic attraction between a positively charged nucleus and its negatively charged electron balances the centrifugal forces of the rapidly revolving electrons and maintains them in their orbits. As a result, the amount of energy required to remove an electron from a given shell must exceed the electrostatic force of attraction between it and the nucleus. The binding energy is characteristic of a given element and shell. To move an electron from an inner orbit to an outer orbit, energy must be supplied in an amount equal to difference in binding energies between the orbits. In contrast, in moving an electron from an outer orbital to one closer to the nucleus, energy is lost and is given up in the form of electromagnetic radiation. Orbital electrons of high atomic number or large atoms have greater binding energies than those in comparable shells of smaller or low atomic number atom. This is because larger atoms have more protons and thus bind the orbital electrons more tightly to the nucleus than do small atoms.

Binding energies of orbital electrons are measured in electron volts (eV) or kilo-electron volts (keV). The amount of energy acquired by one electron in passing through a potential difference of one volt is an electron volt. The energy required to remove an electron from its orbital shell must exceed the binding energy of the electron in that shell. A great amount of energy is required to remove an inner shell electron, but electrons loosely held in the outer shell can be affected by lesser energies, are easier to remove and they take more part in chemical reactions. The binding energies of the K, L and M shells of tungsten are 70 keV, 12 keV and 3 keV respectively. So, in the tungsten atom, to remove a K shell electron, 70 keV of energy would be required where as only 3 keV of energy would be necessary to remove an electron from the M shell. Because the electrons in the inner shells have greater binding energies, it takes X-rays, gamma rays or high-energy particles to remove the electron from these shells. Electrons in the outer shells are not held so tightly to the nucleus and therefore can be affected by lesser energies, such as visible light rays and ultraviolet rays.

IONIZATION

Ionization is the process by which a neutral atom or molecule acquires either a positive or a negative charge. If an orbiting electron receives sufficient energy to be able to escape from the atom completely, this is called ionization of the atom. When an atom loses or gains an electron, it is said to be ionized. An atom that is not electrically balanced is called an ion. In any ionization process, ion pairs are formed and it is this ionization process that elicits chemical changes in the matter. Electrons can move from orbit to orbit if they have sufficient energy. If an electron in an atom is able to take up an orbit of a higher energy, this is termed excitation of the atom. Atoms in an excited state take part in more chemical reactions, which leads to chemical changes in matter.

ISOTOPES

Isotopes are atoms with the same atomic number (Z), but with different atomic mass numbers (A) and hence different numbers of neutrons (N). Isobars have the same atomic mass but different atomic numbers. Radioisotopes are isotopes with unstable nuclei, which undergo radioactive disintegration. Nuclide is a particular variety of atom characterized by a given atomic number and a given mass number or a nucleus with a specific value of Z and A. Radionuclide or radioisotope is any nuclide or isotope, which is radioactive.

Radiation is the transmission of energy through space and matter. Radiation can be two forms. The energy may be non-ionizing and ionizing. If the energy is sufficient to knock out an orbital electron, the energy is ionizing radiation. The two types of ionizing radiations are:

1. **Particulate radiation:** (formerly called corpuscular radiation) comprising alpha particles (helium nuclei), beta particles (negatrons and positrons), cathode rays (electrons), protons and neutrons.
2. **Electromagnetic radiation:** Electromagnetic radiation has both electrical and magnetic properties. It consists of X-rays and gamma rays, ultraviolet rays, visible light, infrared rays (heat), microwaves, radio waves and television waves. X-rays are produced by a machine and gamma rays are produced when radioactive materials decay. Neither of them have any mass.

PARTICULATE RADIATION

Particulate radiations are actually minute particles of matter that travel in straight lines at high speed from their source. Although small, they possess mass and are electrically charged except neutrons. This consists of atomic nuclei or subatomic particles moving at high velocity. The capacity of particulate radiation to ionize an atom depends on its kinetic energy and its charge. Alpha particles, beta particles, and cathode rays are examples of particulate radiation.

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Alpha Particles

Alpha particles are composed of a combination of two protons and two neutrons. It is simply a helium nucleus without orbital electrons. They result from the decay of many radioactive elements. Alpha particles having large mass and two positive charges strongly ionize the atoms of the matter through which they pass. Upon receiving two electrons, an alpha particle becomes a neutral helium atom. Alpha particle leaves the nucleus at high speeds (9,000–18,000 miles/second), but do not penetrate matter for any appreciable depth and give up their large energies within a very short distance in air (5 cm) and in soft tissue (100 μm). In fact, an ordinary sheet of paper absorbs them. For this reason, they are less hazardous externally. However, if they get into the body, they will irradiate the tissues around them intensely, causing serious health hazards. Alpha emitting nuclides are seldom used in medicine. Alpha particles are the least penetrating radiation, yet one of the most damaging over short ranges.

Beta Particles

Electrons have a very small mass compared with protons. We are concerned with only beta particles (negatrons) and cathode rays. Both beta and cathode rays are high-speed electrons.

Beta particles may be negatively charged electrons (negatrons, β–) or positively charged electrons (positrons β+). There is no known difference between the negatron particle and the electron except for their origin. The energetic negatron and positron particles also lose their energy by excitation and ionization of molecules, but because of their smaller mass and charge, their specific ionization is not as high as that of alpha particle. Beta particles are emitted from the nucleus of radioactive atoms and possess one unit of negative charge. The high-speed beta particles are able to penetrate matter to a greater depth than alpha particles to a maximum of 1.2 cm of soft tissues and 10–100 cm of air. This is because beta particles are smaller, lighter and carry a single negative charge. Therefore, they have a much lower probability of interacting with matter than alpha particles. Beta particles are less strongly ionizing than alpha particles. Beta particles are used in radiation therapy for treatment of skin lesions.

Cathode Rays

Cathode rays are streams of high-speed electrons passing from the hot filament of the cathode to the target of the anode in the X-ray tube. They differ from beta particles in their place of origin. Beta particles come from the nucleus of radioactive atoms, whereas cathode rays originate from the orbital electrons of the atoms of the filament material of an X-ray tube.

PROTONS

Protons are accelerated hydrogen nuclei. They are approximately 2,000 times the mass of the electron. Because protons are heavy charged particles, they lose kinetic energy rapidly as they penetrate matter.

NEUTRONS

Neutrons carry no electrical charge and have nearly the same mass as a proton. Neutron being electrically neutral can penetrate into the nucleus of an atom without being subjected to the enormous force of repulsion that resists the entrance of a positively charged particle.

The capacity of particulate radiation to ionize atoms depends on its mass, velocity and charge. The rate of loss of energy from a particle as it moves along the track through matter (tissue) is its linear energy transfer. A particle loses kinetic energy as it ionizes adjacent matter; the greater the physical size and charge the lower its velocity and the greater is its linear energy transfer, e.g. alpha particles, with their high charge and low velocity lose kinetic energy rapidly and have short path lengths (are densely ionizing); thus they have a high linear energy transfer. Beta particles are much less densely ionizing, because of their lighter mass and lower charge and thus have a lower linear energy transfer.

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Key Points

- Physics is a science concerned with study of matter and energy and their interaction with each other.
- Radiation physics is the study of origin, nature and behavior of X-rays and other radiations.
- Universe is made up of matter consisting of solid, liquid or gas which has a mass and can exert force or be acted on by a force.
- Atom is the smallest fundamental unit of elements.
- Atom consists of subatomic particles, protons, electrons and neutrons.
- Energy is the ability to do work, which can be mechanical, electrical, chemical, thermal light, X-rays, etc.
- Much like matter, energy can neither be created nor destroyed and any form of energy can be converted into another form.
- Atoms consist of positively charged nucleus, neutrons and negatively charged electrons in the orbit.
- Number of protons and electrons are equal in an atom and atom remains neutral.
- Electrons are negatively charged particles arranged in orbits or shells known as K, L, etc.
- No known atom has more than seven shells.
- Ionizing radiations are two types, particulate radiation and electromagnetic radiation.
- Particulate radiation consists of alpha particles, beta particles, cathode rays, protons and neutrons.
- Electromagnetic radiation consists of X-rays, gamma rays, ultraviolet rays, visible light, infrared rays, microwaves, radio waves, television waves and radar waves.
- Beta and cathode rays are high-speed electrons.
- Beta particles may be positron or negatron.
- Beta particles are emitted from the nucleus of radioactive atoms.
- Cathode rays are produced from the filament in the X-ray tube.

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Kamala G Pillai has over 40 years of teaching experience in Oral Medicine and Radiology at Schools of Dentistry in India and overseas. Her teaching career started in the College of Dental Surgery, Manipal, India, where she was later promoted to Professor and Head of the Department of Oral Medicine and Radiology. Her experience abroad includes as a Professor, Arab Medical University, Benghazi, Libya; Jordan University of Science and Technology, Irbid, Jordan; and as a Senior Lecturer, University of the West Indies, Trinidad & Tobago. She also worked for a brief period as a Professor, SDM College of Dental Sciences, Dharwad, Karnataka, India.

She has served as an external examiner in the Universities of Mysore, Mangalore, Bangalore, Bombay and Kerala, India. She has supervised the research work of several postgraduate students of Dentistry and has published many scientific research papers in national and international journals. She had the opportunity for professional interaction with the celebrated authors Dr HM Worth and Dr Colin Price at the Faculty of Dentistry, University of British Columbia, Vancouver, BC, Canada; and co-authored research papers with the Faculty of Mouth and Mucosa Clinic at the Vancouver General Hospital, Vancouver, Canada.

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