A 300 Level Course: POST-SIWES SEMESTER

PHYS 350: MEDICAL REACTOR PHYSICS I

Credit: 2 units. Duration of Course: 8 weeks of didactic lectures

Lecturer: Opadele A.E Contact: opadelea@babcock.edu.ng

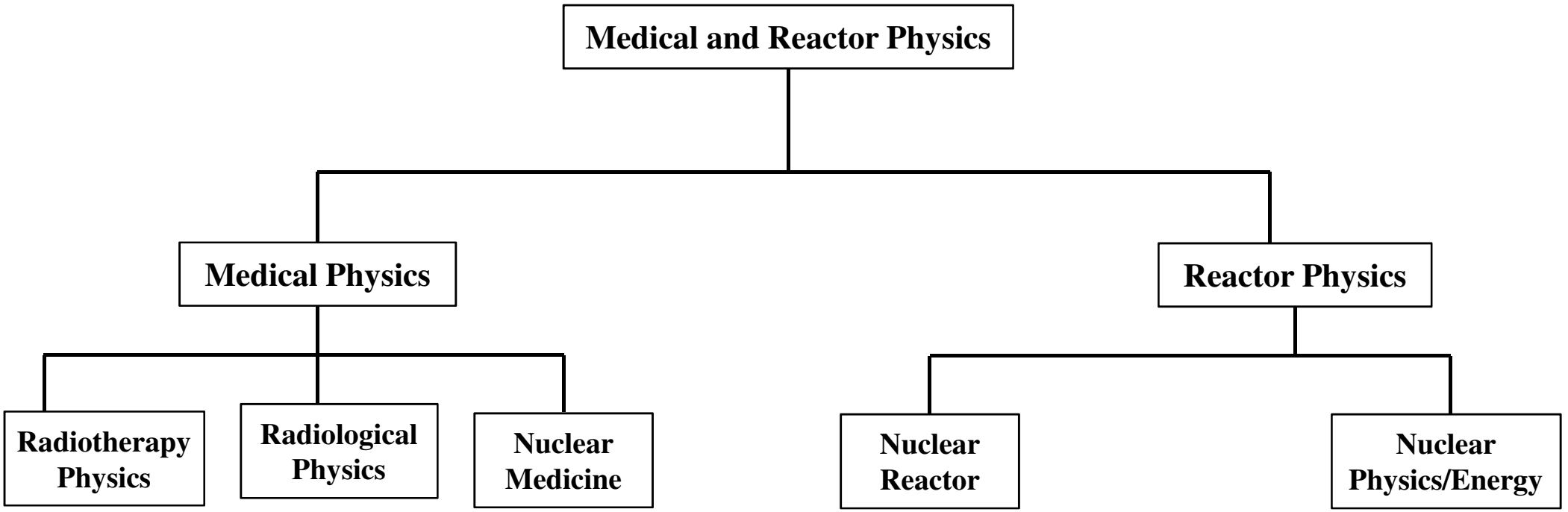
TOPICS

Effects of Radiation on Living Cells: Somatic and Genetic Damages.

Uses of Radiation: Radiation Protection, Principles and Methods.

Personnel Monitoring using TLD and Film.

ORGANOGRAM: INTRO. TO COURSE DESCRIPTION



Introduction to Radiation

Radiation is energy that travels through space or matter.

Radiation may be classified as electromagnetic or particulate, with electromagnetic radiation including visible light, infrared and ultraviolet, X-rays and gamma rays and particulate radiation including electrons, positrons, protons and neutrons.

By particle radiation, we mean energy propagated by traveling corpuscles that have a definite rest mass and within limits have a definite momentum and defined position at any instant.

These particles can travel with high speeds, depending on their kinetic energy, but never attain exactly the speed of light in a vacuum.

Introduction to Radiation

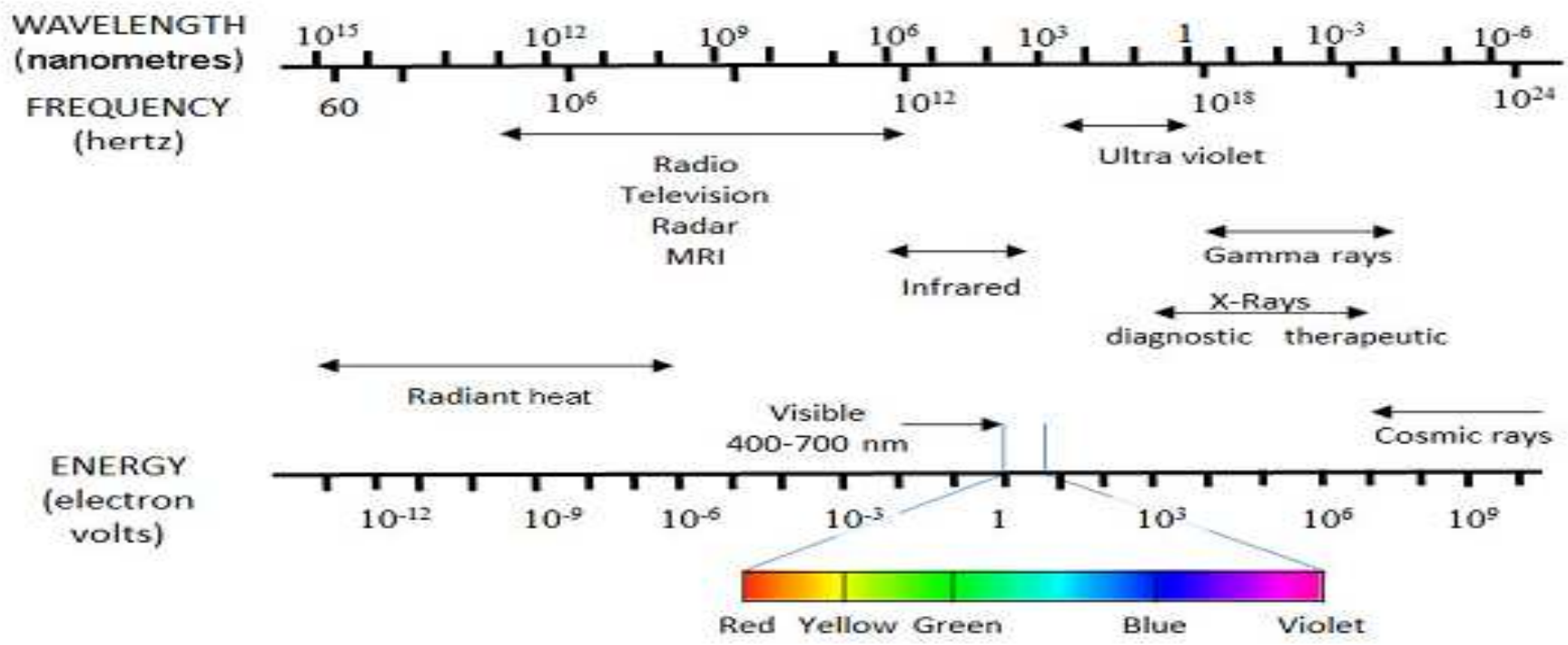


Diagram showing the electromagnetic spectrum

Electromagnetic Radiation

Radio waves, visible light, x-rays, and gamma rays are different types of EM radiation.

Electromagnetic waves can, like all waves, be characterized by their amplitude, wavelength (λ), frequency and speed.

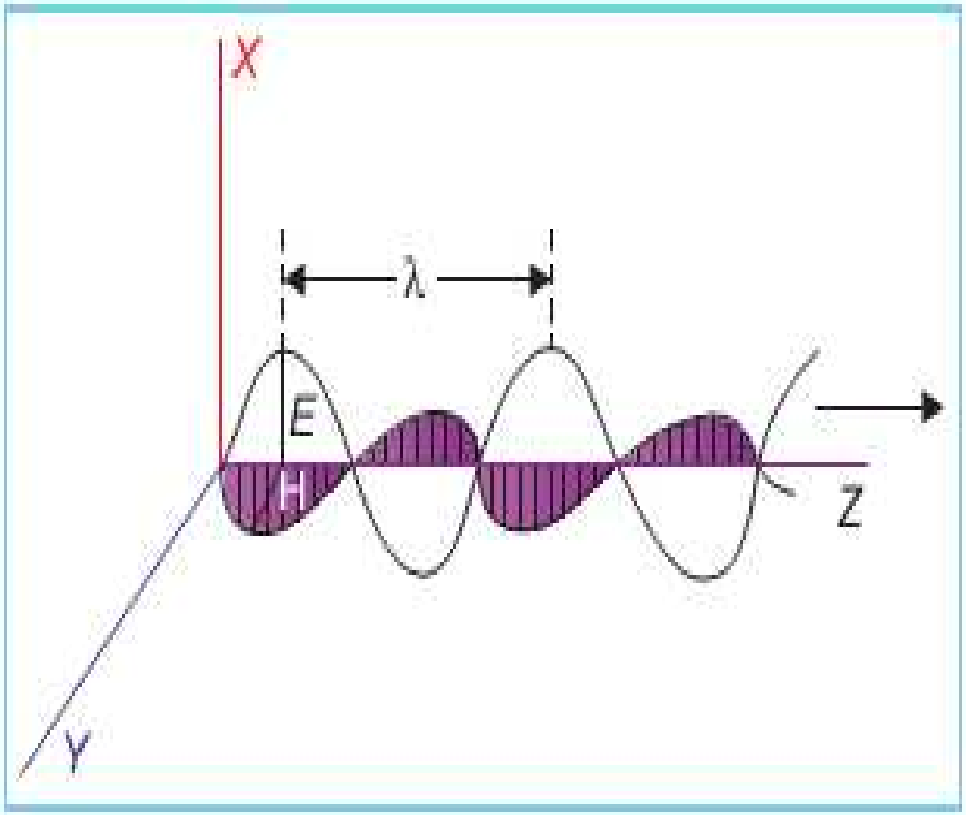
The amplitude is the intensity of the wave.

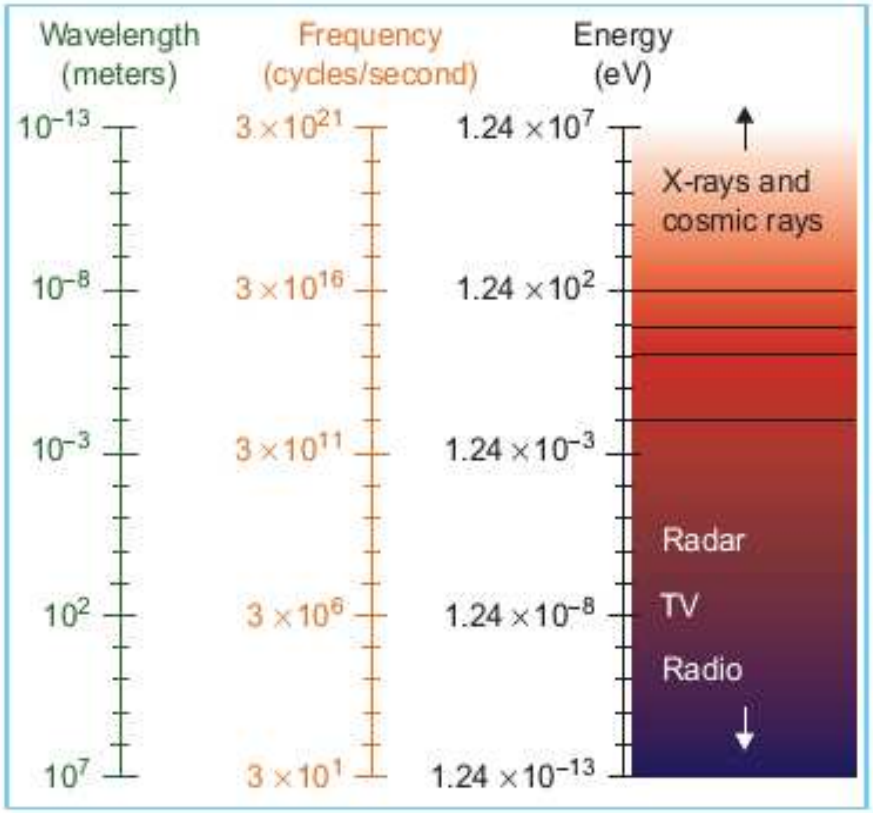
The wavelength is the distance between identical points on adjacent cycles.

The frequency is the number of complete wave oscillations per unit time.

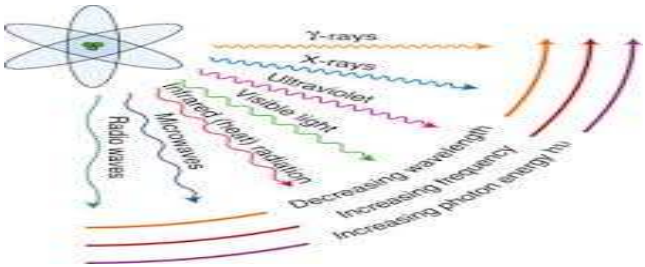
The speed of the wave is equal to the product of the frequency and the wavelength, and its magnitude depends upon the nature of the material through which the wave travels and the frequency of the radiation

Electromagnetic Radiation





Electromagnetic Radiation



EM radiation has no mass, is unaffected by either electric or magnetic fields, and has a constant speed in a given medium.

Although EM radiation propagates through matter, it does not require matter for its propagation.

Its maximal speed (2.998×10^8 m/s) occurs in a vacuum.

In matter such as air, water, or glass, its speed is a function of the transport characteristics of the medium.

EM radiation travels in straight lines; however, its trajectory can be altered by interaction with matter.

Electromagnetic Radiation

Several forms of EM radiation are used in diagnostic imaging.

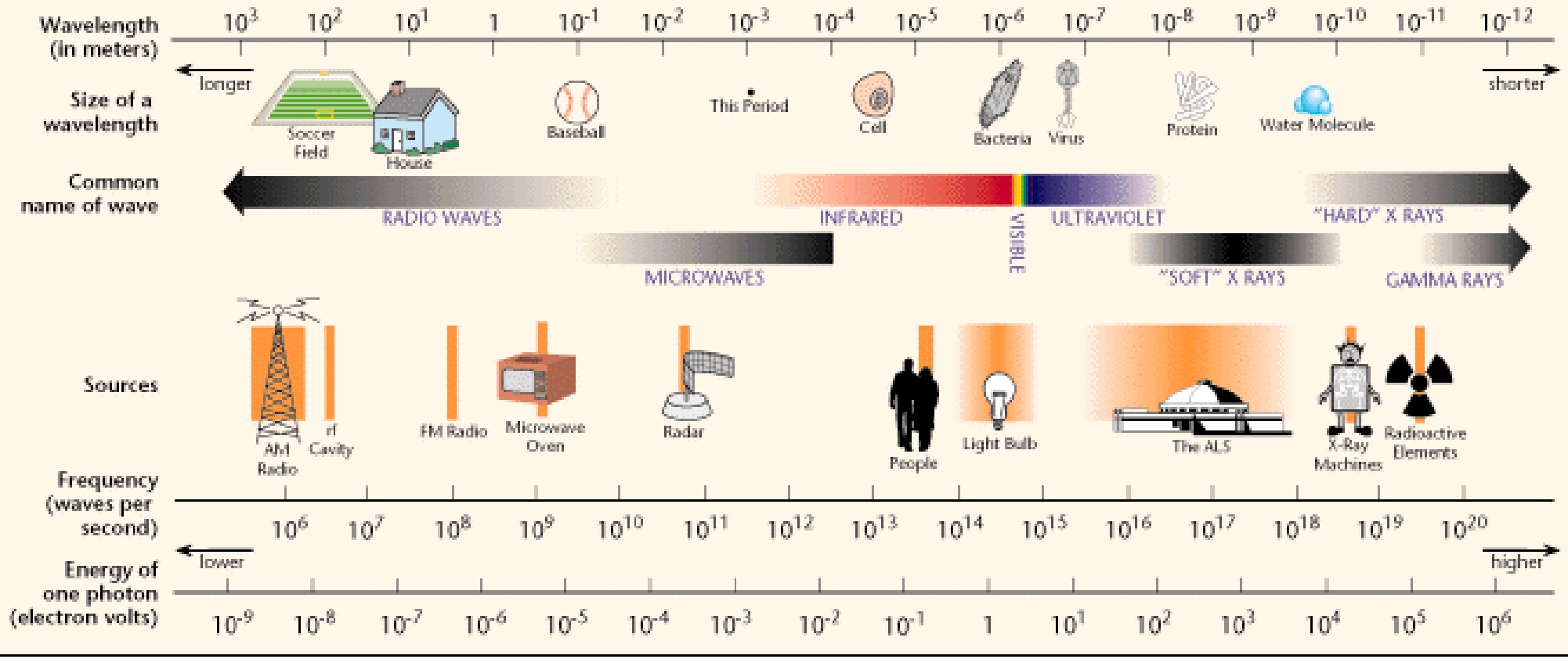
Gamma rays, emitted by the nuclei of radioactive atoms, are used to image the distributions of radiopharmaceuticals.

X-rays, produced outside the nuclei of atoms, are used in radiography, fluoroscopy, and computed tomography.

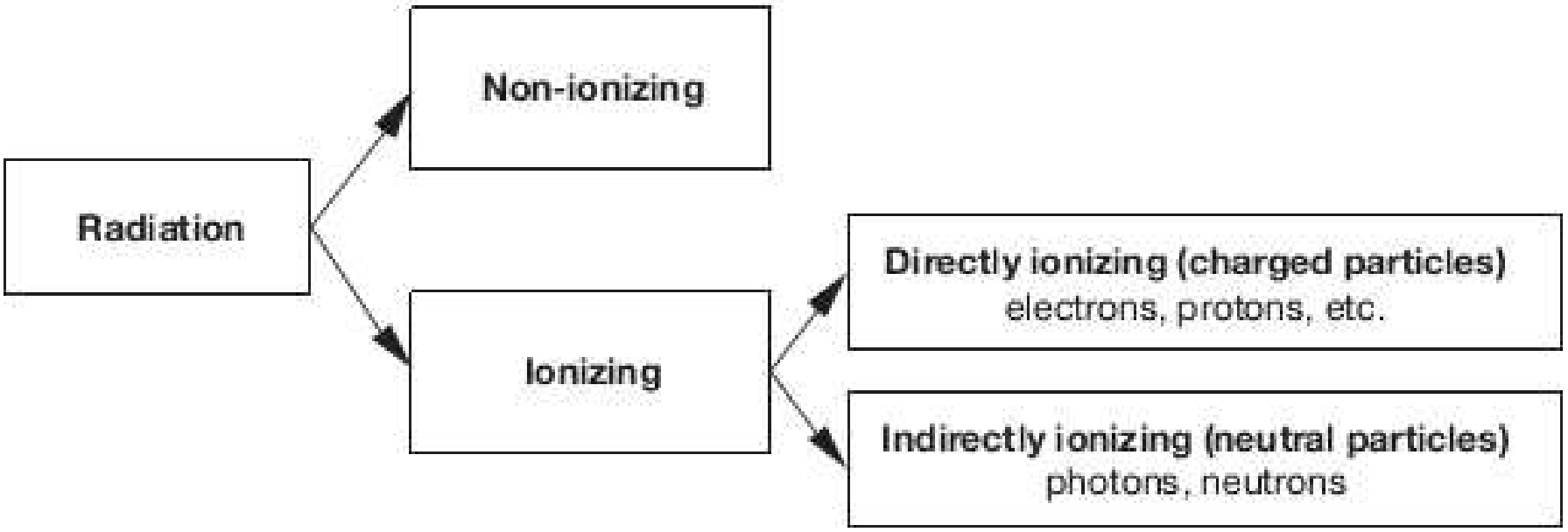
Visible light is produced when x-rays or gamma rays interact with various scintillators in the detectors used in several imaging modalities and is also used to display images.

Radiofrequency EM radiation, near the FM frequency region, is used as the excitation and reception signals for magnetic resonance imaging.

THE ELECTROMAGNETIC SPECTRUM



Radiation: Ionizing and Non-Ionizing



Radiation: Ionizing and Non-Ionizing

-Non-ionizing radiation (cannot ionize matter).

-Ionizing radiation (can ionize matter either directly or indirectly):

—Directly ionizing radiation (charged particles): electrons, protons, α-particles and heavy ions.

—Indirectly ionizing radiation (neutral particles): photons (X rays and γ-rays), neutrons.

Directly ionizing radiation deposits energy in the medium through direct Coulomb interactions between the directly ionizing charged particle and orbital electrons of atoms in the medium.

Indirectly ionizing radiation (photons or neutrons) deposits energy in the medium through a two step process:

Radiation: Ionizing and Non-Ionizing

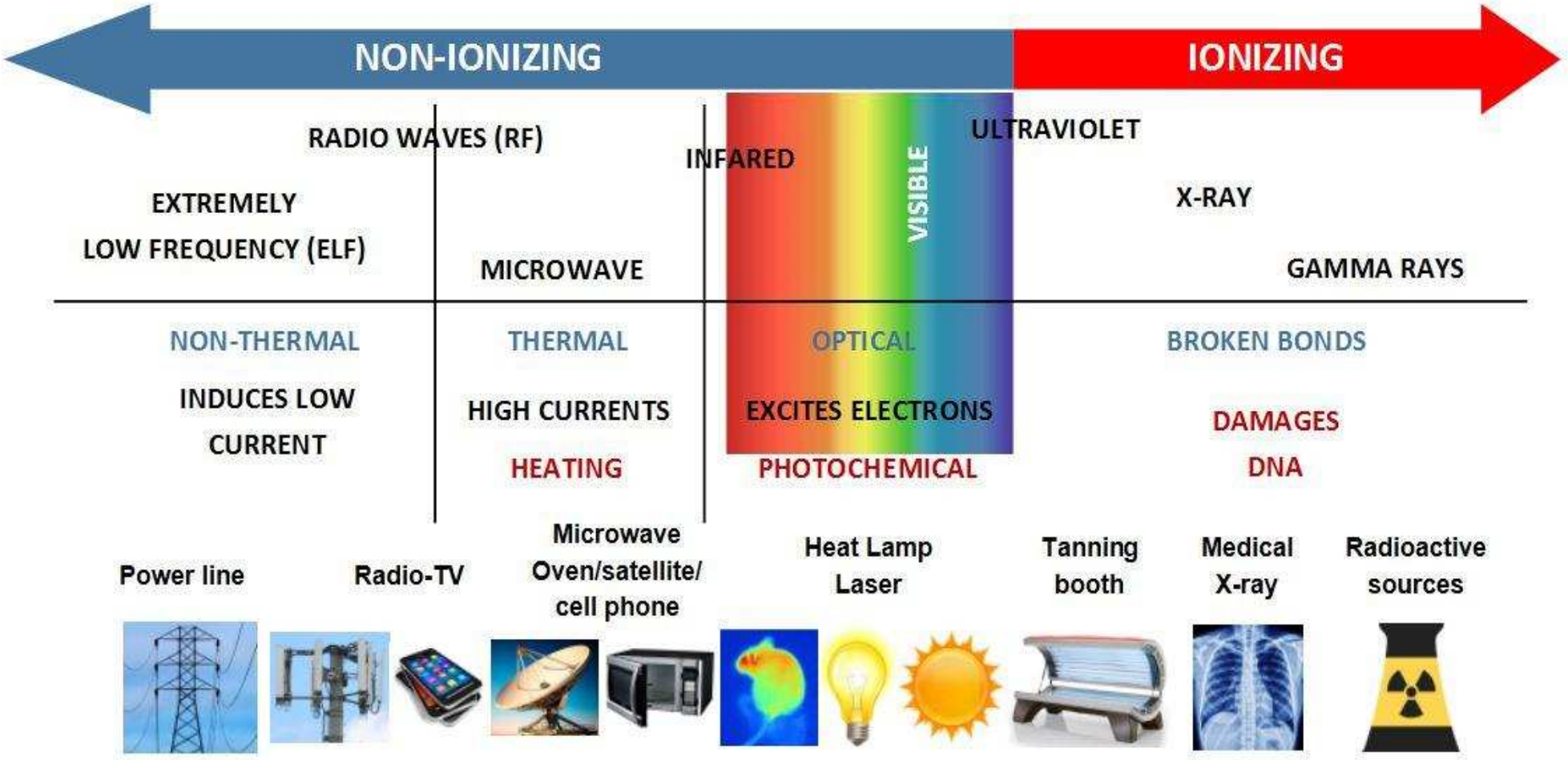
-In the first step a charged particle is released in the medium (photons release electrons or positrons, neutrons release protons or heavier ions);

-In the second step the released charged particles deposit energy to the medium through direct Coulomb interactions with orbital electrons of the atoms in the medium.

Both directly and indirectly ionizing radiations are used in the treatment of disease, mainly but not exclusively for malignant disease.

The branch of medicine that uses radiation in the treatment of disease is called radiotherapy, therapeutic radiology or radiation oncology.

Diagnostic radiology and nuclear medicine are branches of medicine that use ionizing radiation in the diagnosis of disease.


NON-IONIZING
IONIZING
RADIO WAVES (RF)
EXTREMELY LOW FREQUENCY (ELF)
MICROWAVE
INFARED
VISIBLE
ULTRAVIOLET
X-RAY
GAMMA RAYS
NON-THERMAL
INDUCES LOW CURRENT
THERMAL
HIGH CURRENTS
HEATING
OPTICAL
EXCITES ELECTRONS
PHOTOCHEMICAL
BROKEN BONDS
DAMAGES
DNA
Power line
Radio-TV
Microwave Oven/satellite/ cell phone
Heat Lamp Laser
Tanning booth
Medical X-ray
Radioactive sources

Curled from The Essential Physics of Medical Imaging by Bushberg

Particulate Radiation

TABLE 2-1 PROPERTIES OF PARTICULATE RADIATION

PARTICLE	SYMBOL	ELEMENTARY CHARGE	REST MASS (amu)	ENERGY EQUIVALENT (MeV)
Alpha	α, $^4He^{2-}$	+2	4.00154	3,727
Proton	p, $^1H^+$	+1	1.007276	938
Electron	e^-	−1	0.000549	0.511
Negatron (beta minus)	β^-	−1	0.000549	0.511
Positron (beta plus)	β^+	+1	0.000549	0.511
Neutron	n^0	0	1.008665	940

amu, atomic mass unit , defined as 1/12th the mass of a carbon-12 atom. Elementary charge is a unit of electric charge where 1 is equal in magnitude to the charge of an electron.

Radiation Effects

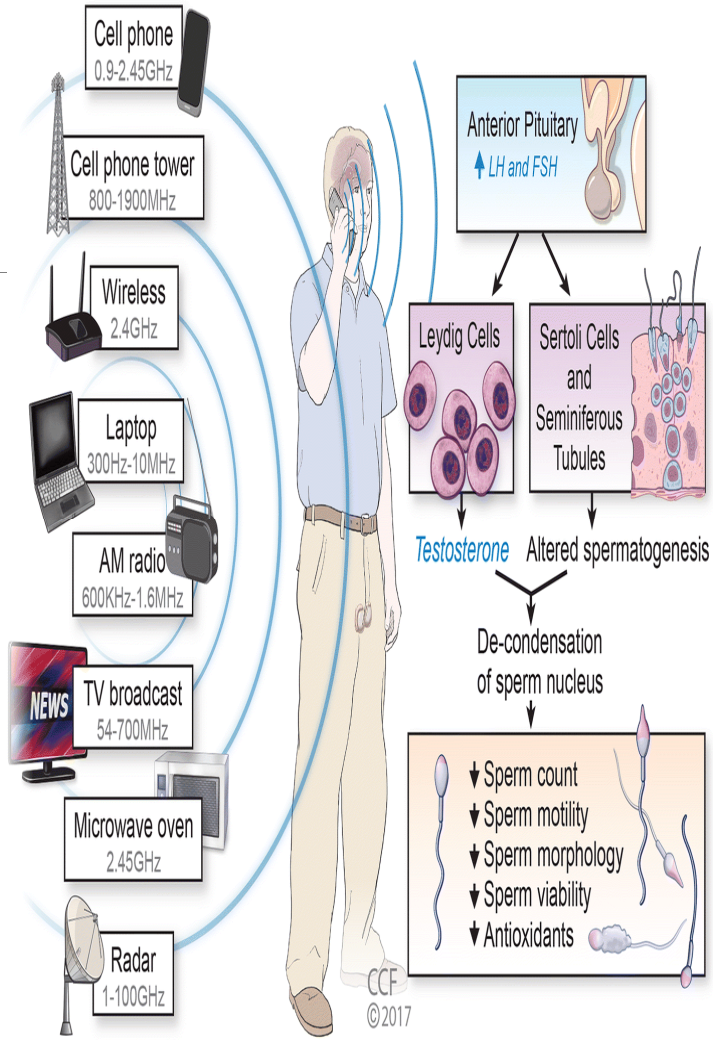
Radiobiology, a branch of science concerned with the action of ionizing radiation on biological tissues and living organisms, is a combination of two disciplines: radiation physics and biology.

All living things are made up of protoplasm, which consists of inorganic and organic compounds dissolved or suspended in water.

The smallest unit of protoplasm capable of independent existence is the cell.

Cells contain inorganic compounds (water and minerals) as well as organic compounds (proteins, carbohydrates, nucleic acids and lipids).

The two main constituents of a cell are the cytoplasm, which supports all metabolic functions within the cell, and the nucleus, which contains the genetic information (DNA).



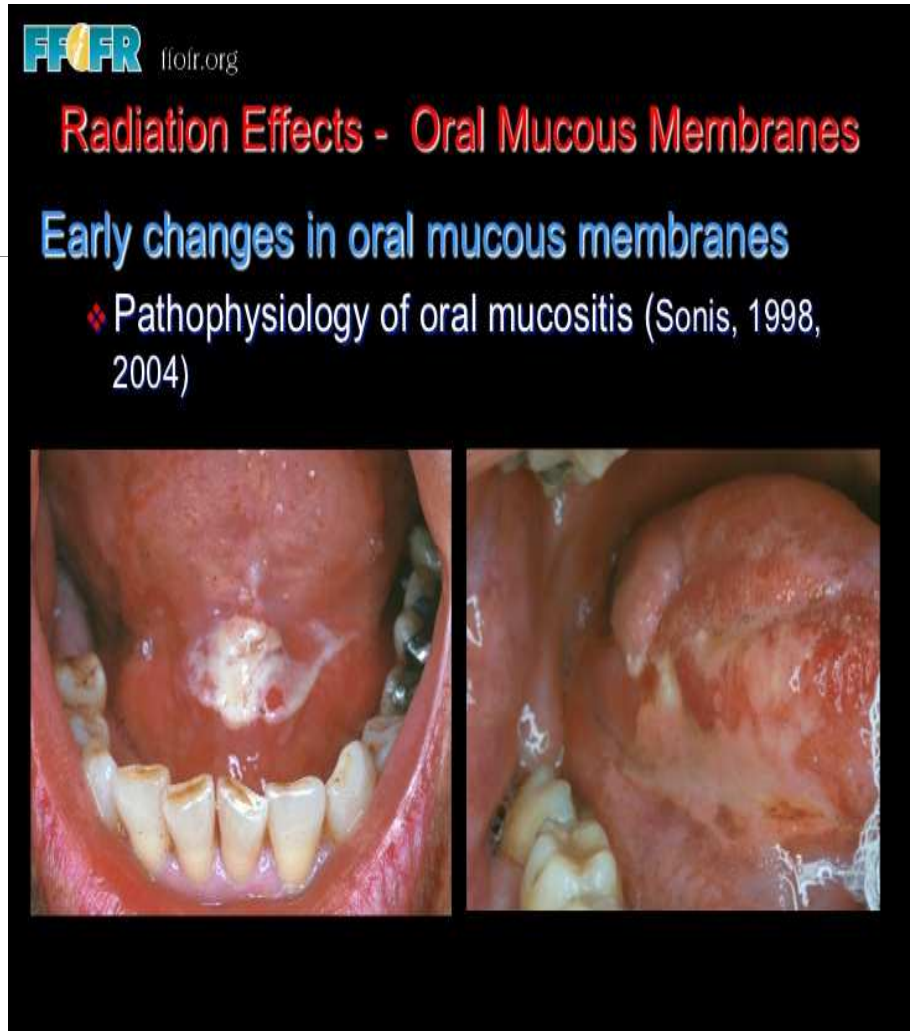
Radiation Effects

Human cells are either somatic cells or germ cells.

Cells propagate through division: division of somatic cells is called mitosis, while division of germ cells is called meiosis.

When a somatic cell divides, two cells are produced, each carrying a chromosome complement identical to that of the original cell.

The new cells themselves may undergo further division, and the process continues.



Radiation Effects

Somatic cells are classified as:

-Stem cells, which exist to self-perpetuate and produce cells for a differentiated cell population (e.g. stem cells of the hematopoietic system, epidermis and mucosal lining of the intestine).

-Transit cells, which are cells in movement to another population (e.g. a reticulocyte that is differentiating to become an erythrocyte).

-Mature cells, which are fully differentiated and do not exhibit mitotic activity (e.g. muscle cells and nervous tissue).

A group of cells that together perform one or more functions is referred to as tissue.

A group of tissues that together perform one or more functions is called an organ.

A group of organs that perform one or more functions is a system of organs or an organism

Classifications of Radiation in Radiobiology

For use in radiobiology and radiation protection the physical quantity that is useful for defining the quality of an ionizing radiation beam is the linear energy transfer (**LET**).

LET focuses attention on the linear rate of energy absorption by the absorbing medium as the charged particle traverses the medium.

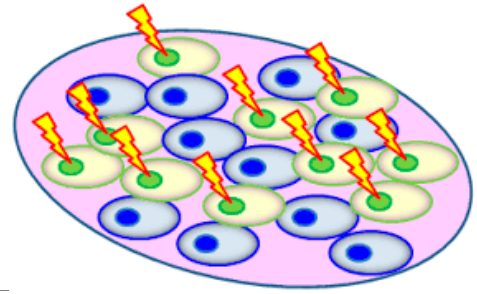
The ICRU defines the LET as follows:

"LET of charged particles in a medium is the quotient dE/dl, where dE is the average energy locally imparted to the medium by a charged particle of specified energy in traversing a distance of dl.

The unit for LET is $KeV/\mu m$.

X rays and grays are considered low LET (sparsely ionizing) radiations, while energetic neutrons, protons and heavy charged particles are high LET (densely ionizing) radiations.

IRRADIATION OF CELLS



When cells are exposed to ionizing radiation the standard physical effects between radiation and the atoms or molecules of the cells occur first and the possible biological damage to cell functions follows later.

The biological effects of radiation result mainly from damage to the DNA, which is the most critical target within the cell; however, there are also other sites in the cell that, when damaged, may lead to cell death.

When directly ionizing radiation is absorbed in biological material, the damage to the cell may occur in one of two ways: direct or indirect.

Direct Action in Cell Damage by Radiation

In direct action the radiation interacts directly with the critical target in the cell. The atoms of the target itself may be ionized or excited through Coulomb interactions, leading to the chain of physical and chemical events that eventually produce the biological damage.

Direct action is the dominant process in the interaction of high LET particles with biological material.

Indirect Action in Cell Damage by Radiation

In indirect action the radiation interacts with other molecules and atoms (mainly water, since about 80% of a cell is composed of water) within the cell to produce free radicals, which can, through diffusion in the cell, damage the critical target within the cell.

In interactions of radiation with water, short lived yet extremely reactive free radicals such as $H_2 0^+$(water ion) and OH• (hydroxyl radical) are produced. The free radicals in turn can cause damage to the target within the cell.

The free radicals that break the chemical bonds and produce chemical changes that lead to biological damage are highly reactive molecules because they have an unpaired valence electron.

About two thirds of the biological damage by low LET radiations (sparsely ionizing radiations) such as X rays or electrons is due to indirect action.

Indirect action can be modified by chemical sensitizers or radiation protectors

Indirect Action in Cell Damage by Radiation

The steps involved in producing biological damage by the indirect action of X-rays are as follows:

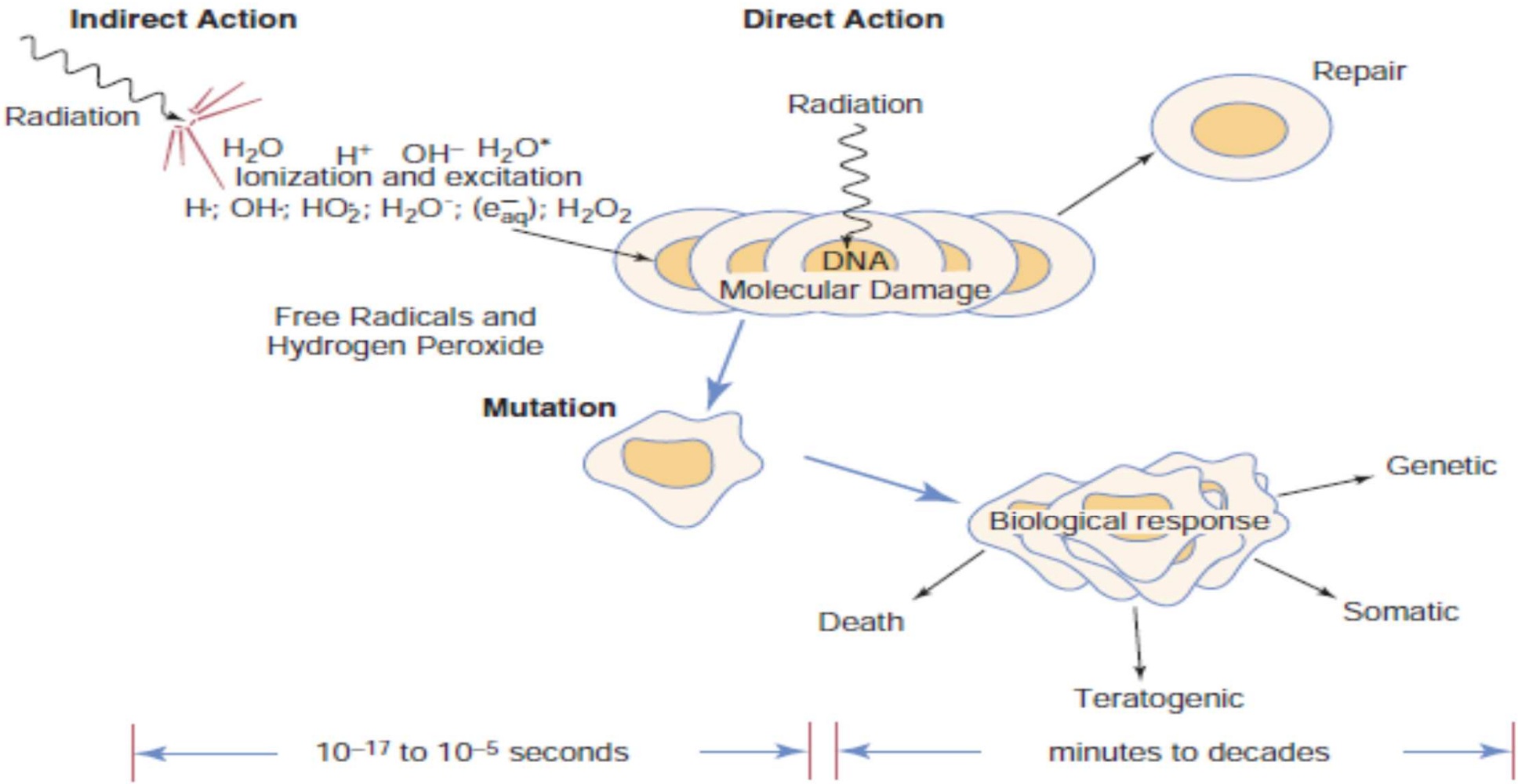
Step 1: Primary photon interaction (photoelectric effect, Compton effect and pair production) produces a high energy electron.

Step 2: The high energy electron in moving through tissue produces free radicals in water.

Step 3: The free radicals may produce changes in DNA from breakage of chemical bonds.

Step 4: The changes in chemical bonds result in biological effects.

Step (1) is in the realm of physics; step (2) is in chemistry; steps (3) and (4) are in radiobiology.


Indirect Action
Direct Action
Radiation
H_2O H^+ OH^- H_2O^*
Ionization and excitation
H·; OH·; $HO_2^·$; H_2O^-; (e^-_{aq}); H_2O_2
Radiation
Repair
DNA
Molecular Damage
Free Radicals and
Hydrogen Peroxide
Mutation
Genetic
Biological response
Death
Somatic
Teratogenic
10^{-17} to 10^{-5} seconds
minutes to decades

Fate of irradiated cells

Irradiation of a cell will result in one of the following **nine possible** outcomes:

1) No effect.

2) Division delay: The cell is delayed from going through division.

3) Apoptosis: The cell dies before it can divide or afterwards by fragmentation into smaller bodies, which are taken up by neighbouring cells.

4) Reproductive failure: The cell dies when attempting the first or subsequent mitosis.

5) Genomic instability: There is a delayed form of reproductive failure as a result of induced genomic instability.

Fate of irradiated cells

6)Transformation: The cell survives but the mutation leads to a transformed phenotype and possibly carcinogenesis.

7) Bystander effects: An irradiated cell can send signals to neighbouring un-irradiated cells and induce genetic damage in them.

8) Adaptive responses: The irradiated cell is stimulated to react and become more resistant to subsequent irradiation.

Image Credit: National Cancer Institute

Fig A = Skin toxicity grade 1 from fluoroscopic procedures.

Fig B = Slight erythema from radionuclide contamination.

Fig C = Epilation from high dose perfusion CT-scan.

Fig D = Skin toxicity grade 3 following cardiac catheterization.

Fig E = Dry desquamation.

Fig F-H = Skin toxicity grade 4 following radiation induced skin injury from fluoroscopy.

Classification of Radiation Damage

Radiation damage to mammalian cells is divided into three categories:

1) Lethal damage: which is irreversible and irreparable and leads to cell death.

2) Sub-lethal damage: which can be repaired in hours unless additional sub-lethal damage is added that eventually leads to lethal damage.

3) Potentially lethal damage: which can be manipulated by repair when cells are allowed to remain in a non-dividing state.

Somatic and Genetic Effects

The effects of radiation on the human population can be classified as either somatic or genetic:

1) Somatic effects are *harm* that exposed individuals suffer during their lifetime, such as radiation induced cancers (carcinogenesis), sterility, opacification of the eye lens and life shortening.

2) Genetic or hereditary effects are radiation induced mutations to an individual's genes and DNA that can contribute to the birth of defective descendants.

Somatic and Genetic Effects

Carcinogenesis expresses itself as a late somatic effect in the form of acute or chronic myeloid leukaemia or some solid tumours, for example in the skin, bone, lung, thyroid or breast.

Human data on carcinogenesis have been collected from the following sources:

— Low level occupational exposure.

— Atomic bomb survivors in Hiroshima and Nagasaki.

— Medical radiation exposure of patients (e.g. during treatment of ankylosing spondylitis, treatment of thyroid abnormalities and radiotherapy of cancer) and staff (e.g. radiologists in the early part of the last century).

RADIATION PROTECTION

Wrapped up in a lead-suit.

Soon after the discovery of X rays by Roentgen in 1895 and of natural radioactivity by Becquerel in 1896 it became apparent that ionizing radiation was not only useful for the diagnosis and treatment of disease but also harmful to human tissues.

It has been recognized since early studies on X-rays and radioactive minerals that exposure to high levels of radiation can cause clinical damage to tissues of the human body.

In addition, long term epidemiological studies of populations exposed to radiation, especially the survivors of the atomic bombings of Hiroshima and Nagasaki in Japan in 1945, have demonstrated that exposure to radiation also has a potential for delayed effects such as induction of malignancies or damage to genetic material.

Radiation Protection

The acceptance by society of the risks associated with radiation is conditional on the benefits to be gained from the use of radiation.

Nonetheless, the risks must be restricted and protected against by the application of radiation safety standards (RSS).

It is therefore essential that activities involving radiation exposure be subject to certain standards of safety in order to protect the individuals who are exposed to radiation, be it occupationally, for medical diagnostic or therapeutic purposes, or as members of the public.

Radiation exposure limits or standards were introduced as early as the start of the 20^{th} century when the potential hazards of radiation were realized

Radiation Protection

Regulatory and International bodies strives for standardization in the peaceful use of atomic energy for scientific development.

- International Commission on Radiological Protection (ICRP)
- National Council on Radiation Protection and Measurements (NCRP)
- International Commission on Radiation Units (ICRU)
- Nuclear Regulatory Commission (NRC).
- International Atomic Energy Agency (IAEA).
- Nigerian Nuclear Regulatory Authority (NNRA)
- Ghana Atomic Energy Agency (GAEC)

INTERNATIONAL CONSENSUS AND RADIATION SAFETY STANDARDS

Safety standards are based on knowledge of radiation effects and on the principles of protection described below.

The United Nations Scientific Committee on the Effects of Atomic Radiation **(UNSCEAR),** a body set up by the United Nations in 1955, compiles, assesses and disseminates information on the health effects of radiation and on levels of radiation exposure due to different sources.

Following a decision made in 1960, the IAEA safety standards are based on the recommendations of the ICRP, which also take account of the scientific information provided by UNSCEAR.

The safety standards implicitly encourage decision makers to make value judgements about the relative importance of risks of different kinds and about the balancing of risks and benefits.

INTERNATIONAL CONSENSUS AND RADIATION SAFETY STANDARDS

The current version of the safety standard entitled International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (hereinafter referred to as the BSS) was issued in 1996 under the joint sponsorship of the Food and Agriculture Organization of the United Nations, IAEA, International Labour Organization, OECD Nuclear Energy Agency, Pan American Health Organization and World Health Organization.

PERSONNEL DOSIMETRY

The radiation exposures of some people must be monitored for both safety and regulatory purposes.

Such assessments may need to be made over periods of several minutes to several months.

There are three main types of individual radiation recording devices called **personnel dosimeters** used in diagnostic radiology and nuclear medicine:

(1) Film badges

(2) Dosimeters using storage phosphors (e.g., thermoluminescent dosimeters [TLDs]).

(3) Pocket dosimeters

Personnel Dosimetry: Film Badge

Personnel Dosimetry: Film Badge

A film badge consists of a small sealed packet of radiation sensitive film, similar to dental x-ray film, placed inside a special plastic holder that can be clipped to clothing.

Most film badges can record doses from about 100 μSv to 15 Sv (10 mrem to 1,500 rem) for photons and from 500 μSv to 10 Sv (50 mrem to 1,000 rem) for beta radiation.

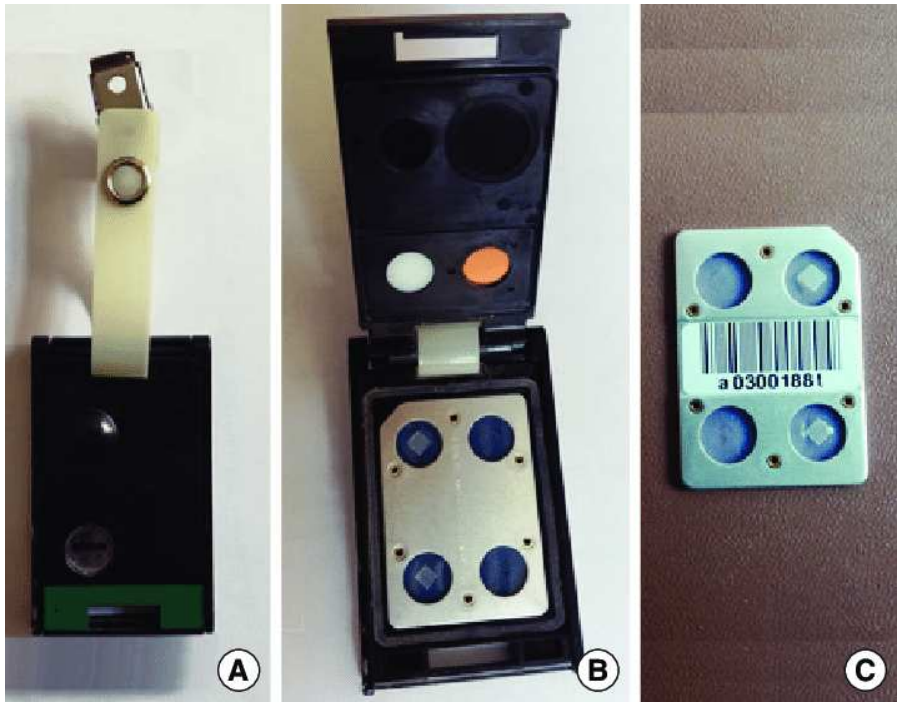
The film in the badge is usually replaced monthly and sent to the commercial supplier for processing.

The developed film is usually kept by the vendor, providing a permanent record of radiation exposure.

Film badges are small, lightweight, inexpensive, and easy to use.

However, exposure to excessive moisture or temperature can damage the film emulsion, making dose estimates difficult or impossible.

Personnel Dosimetry: TLD



Personnel Dosimetry: TLD

TLD are excellent personnel and environmental dosimeters; however, they are somewhat more expensive than film badges.

The most commonly used TLD material for personnel dosimetry is lithium fluoride (LiF). LiF TLDs have a wide dose response range of 100 μSv to 10 Sv and are reusable.

These dosimeters can be used over a long time interval (up to 6 months if necessary) before being returned to the vendor for analysis.

An advantage of LiF TLDs is that their effective atomic number is close to that of the tissue; therefore, the dose to the LiF chip is close to the tissue dose over a wide energy range.

TLDs do not provide a permanent record, because heating the chip to read the exposure removes the deposited energy.

Personnel Dosimetry: Pocket Dosimeter

Personnel Dosimetry: Pocket Dosimeter

Pocket dosimeters measure radiation exposure and can be read immediately.

The major disadvantage to film, thermoluminescent, and OSL dosimeters is that the accumulated dose is not immediately displayed.

Pocket dosimeters can be utilized when high doses are expected, such as during cardiac catheterization or manipulation of large quantities of radioactivity.

Common problems associated with dosimetry include dosimeters being left in radiation fields when not worn, contamination of a dosimeter itself with radioactive material, lost and damaged dosimeters, and people not wearing dosimeters when working with radiation sources.

TABLE 21-2 SUMMARY OF PERSONNEL MONITORING METHODS

METHOD	MEASURES	USEFUL RANGE (X-AND GAMMA RAY)	PERMANENT RECORD	USES AND COMMENTS
Film badge	Beta; gamma and x-ray	0.1–15,000 mSv[a] (beta) 0.5–10,000 mSv[a]	Yes	Routine personnel monitoring; most common in diagnostic radiology and nuclear medicine
TLD	Beta; gamma and x-ray	0.01–10^6 mSv[a]	No	Becoming more common but still more expensive than film; used for phantom and patient dosimetry
OSL	Beta; gamma and x-ray	0.01–10^6 mSv[a]	No[b]	Advantage over TLD includes the ability to reread the dosimeters and distinguish between dynamic and static exposures
Pocket dosimeter	Gamma and x-ray	Analog: 0–0.2 R, 0–0.5 R, 0–5 R Digital: 0–100 mSv[a]	No	Special monitoring (e.g., cardiac cath); permits direct (i.e., real-time) reading of exposure

[a]Multiply mSv by 100 to obtain mrem.
[b]OSL dosimeters are typically retained and can be reread by the manufacturer for approximately 1 year.
OSL, optically stimulated luminance; TLD, thermoluminescent dosimeter.

Interaction of Radiation with Matter: X-ray and Gamma Interactions

When traversing matter, photons will penetrate without interaction, scatter, or be absorbed.

There are four major types of interactions of x-ray and gamma-ray photons with matter, the first three of which play a role in diagnostic radiology and nuclear medicine

(a) Rayleigh scattering

(b) Compton scattering

(c) Photoelectric absorption

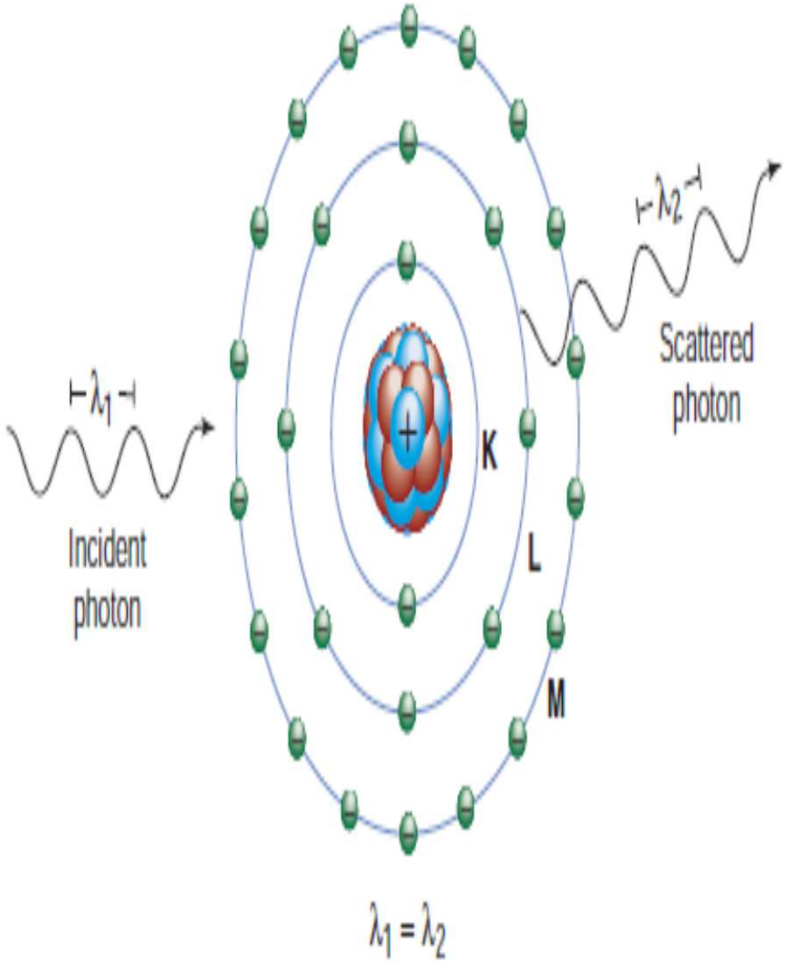
(d) Pair production

Rayleigh Scattering

In Rayleigh scattering, the incident photon interacts with and excites the *total atom,* as opposed to individual electrons as in Compton scattering or the photoelectric effect.

This interaction occurs mainly with very low energy x-rays, such as those used in mammography (15 to 30 keV).

During the Rayleigh scattering event, the electric field of the incident photon's electromagnetic wave expends energy, causing all of the electrons in the scattering atom to oscillate in phase.



Rayleigh Scattering

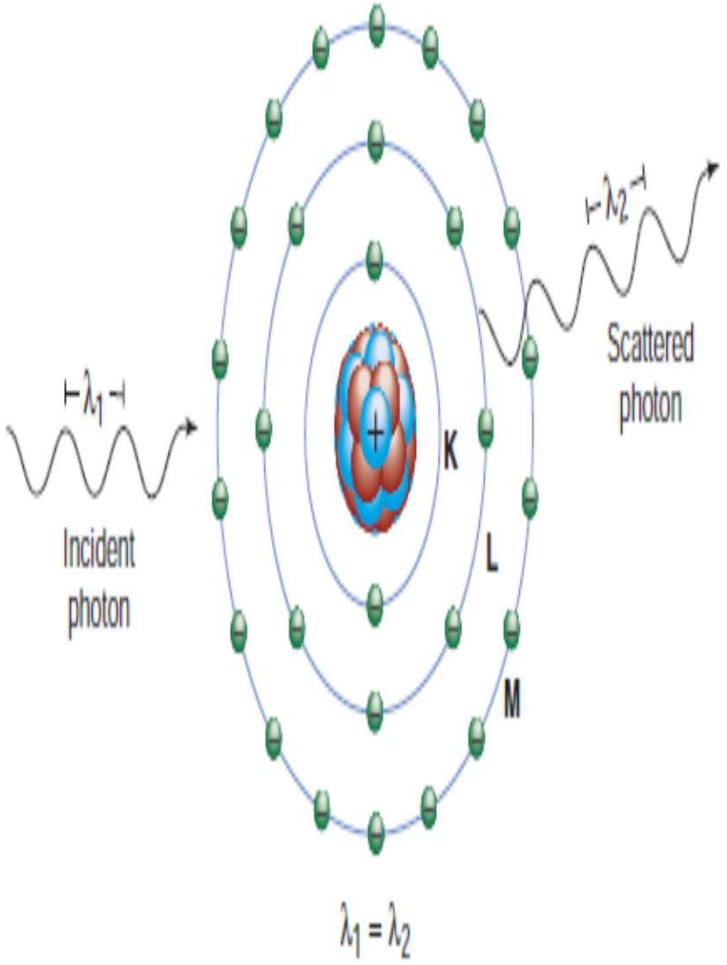
The atom's electron cloud immediately radiates this energy, emitting a photon of the same energy but in a slightly different direction.

In this interaction, electrons are not ejected, and thus, ionization does not occur.

In medical imaging, detection of the scattered x-ray will have a deleterious effect on image quality.

However, this type of interaction has a low probability of occurrence in the diagnostic energy range.

Rayleigh interactions are also referred to as "coherent" or "classical" scattering

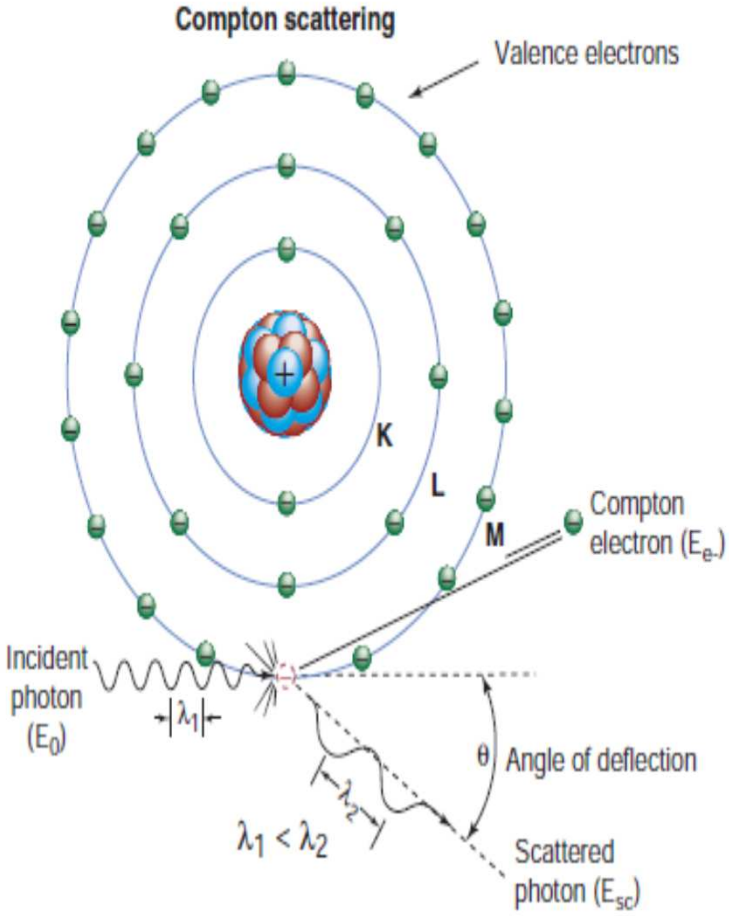


Compton Scattering.

Compton scattering (also called inelastic or non-classical scattering) is the predominant interaction of x-ray and gamma-ray photons in the diagnostic energy range with soft tissue.

In fact, Compton scattering not only predominates in the diagnostic energy range above 26 keV in soft tissue but also continues to predominate well beyond diagnostic energies to approximately 30 MeV.

This interaction is most likely to occur between photons and outer ("valence")-shell electrons.

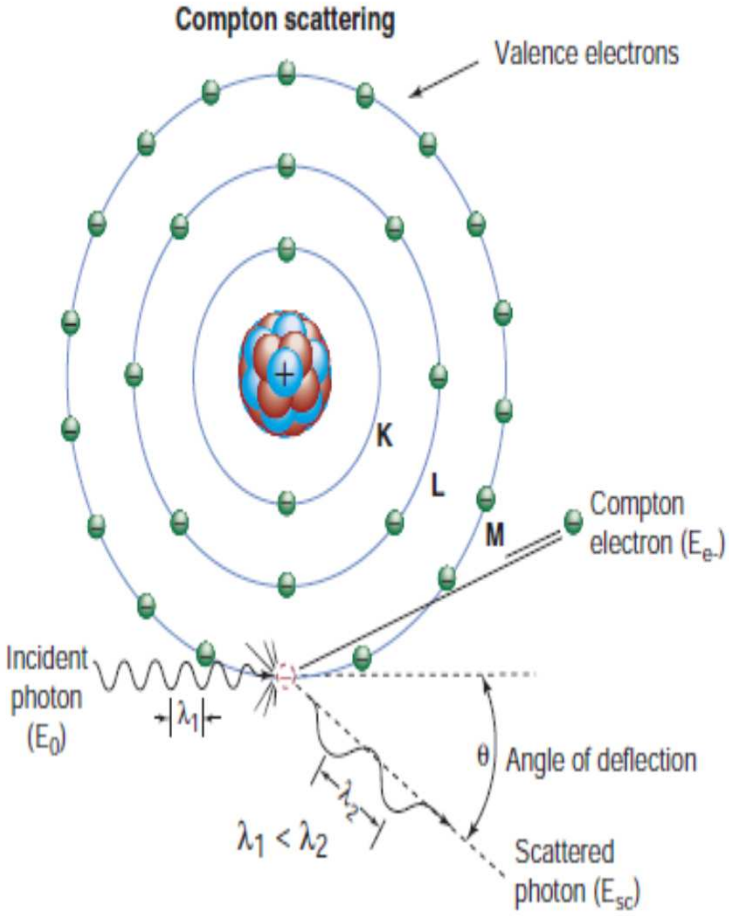


Compton Scattering.

The electron is ejected from the atom, and the scattered photon is emitted with some reduction in energy relative to the incident photon. As with all types of interactions, both energy and momentum must be conserved.

Thus, the energy of the incident photon (E_0) is equal to the sum of the energy of the scattered photon (E_{sc}) and the kinetic energy of the ejected electron (E_e-).

$$E_0 = E_{sc} + E_e-$$

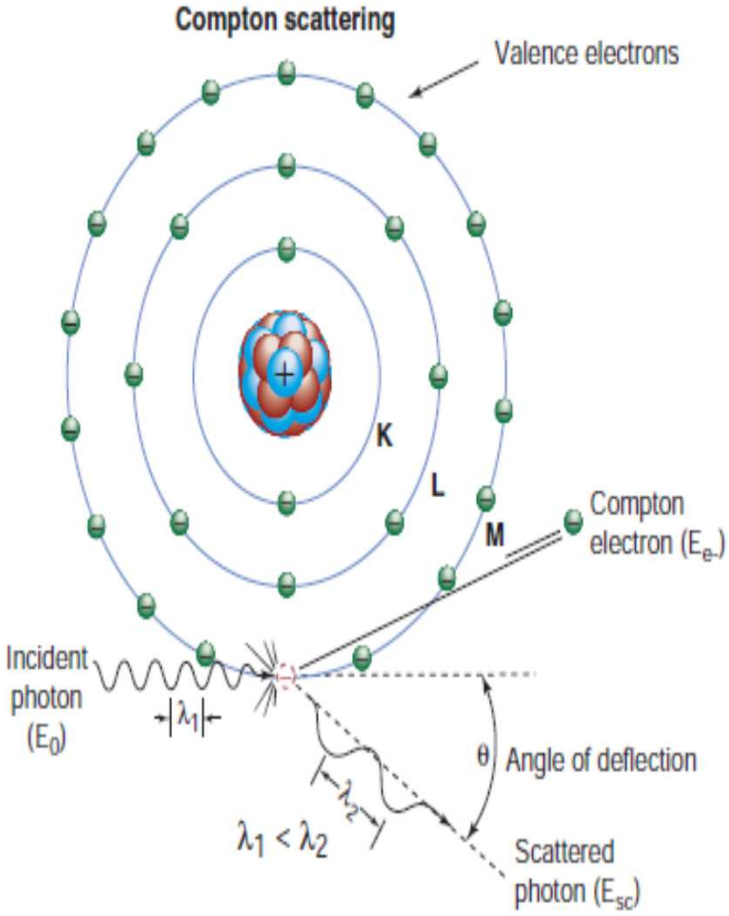


Compton Scattering.

Compton scattering results in the ionization of the atom and a division of the incident photon's energy between the scattered photon and the ejected electron.

The ejected electron will lose its kinetic energy via excitation and ionization of atoms in the surrounding material.

$$E_{sc} = \frac{E_o}{1 + \frac{E_o}{511\ keV}(1 - \cos\theta)}$$



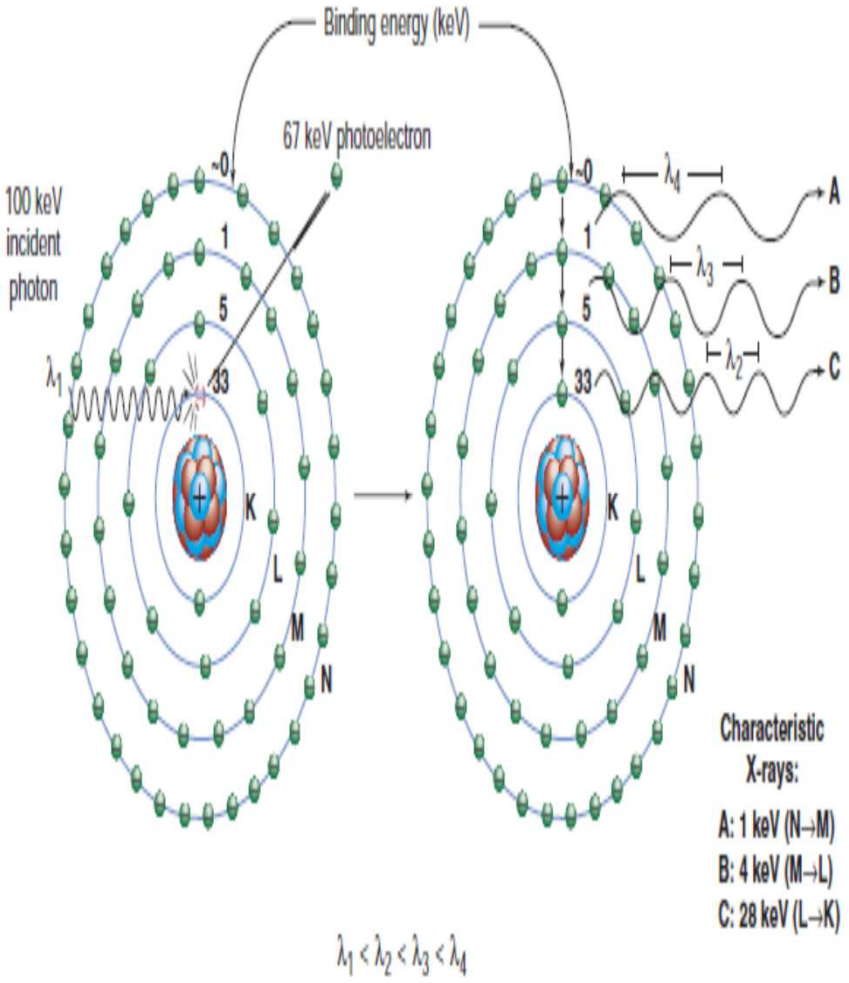
Photoelectric Effect

In the photoelectric effect, all of the incident photon energy is transferred to an electron, which is ejected from the atom.

The kinetic energy of the ejected *photoelectron* (E_{pe}) is equal to the incident photon energy (E_0) minus the binding energy of the orbital electron (E_b).

$$E_{pe} = E_0 - E_b$$

In order for photoelectric absorption to occur, the incident photon energy must be greater than or equal to the binding energy of the electron that is ejected



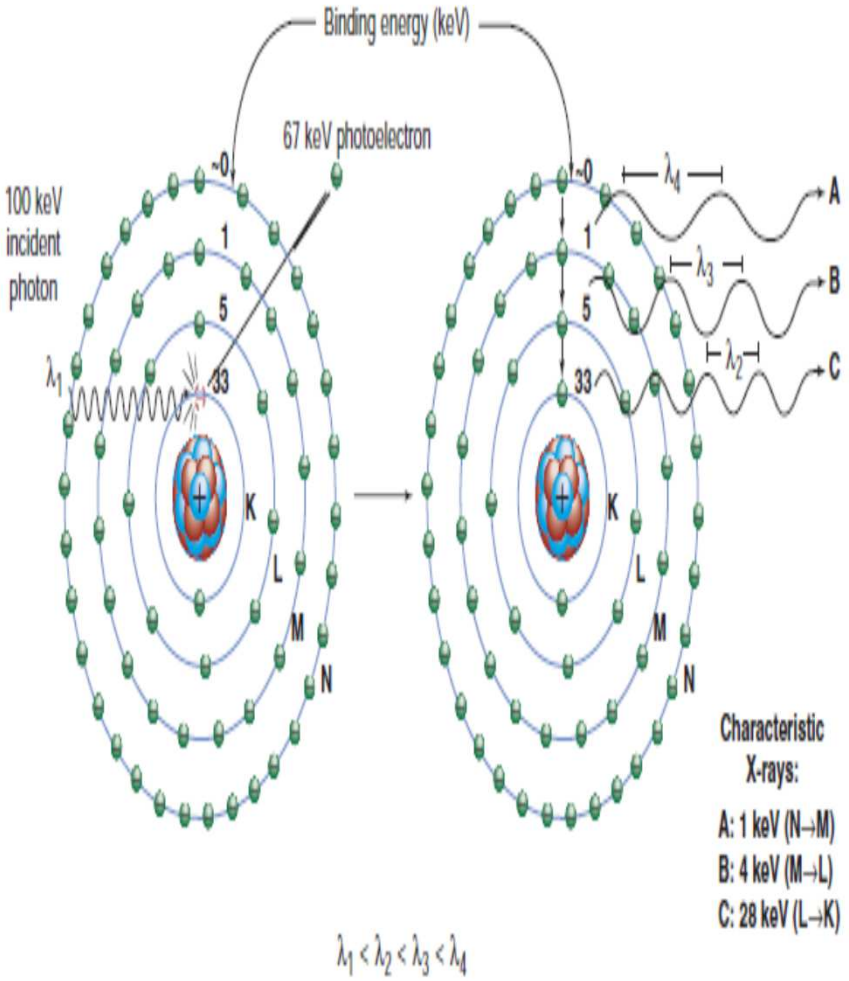
Photoelectric Effect

Following a photoelectric interaction, the atom is ionized, with an inner-shell electron vacancy.

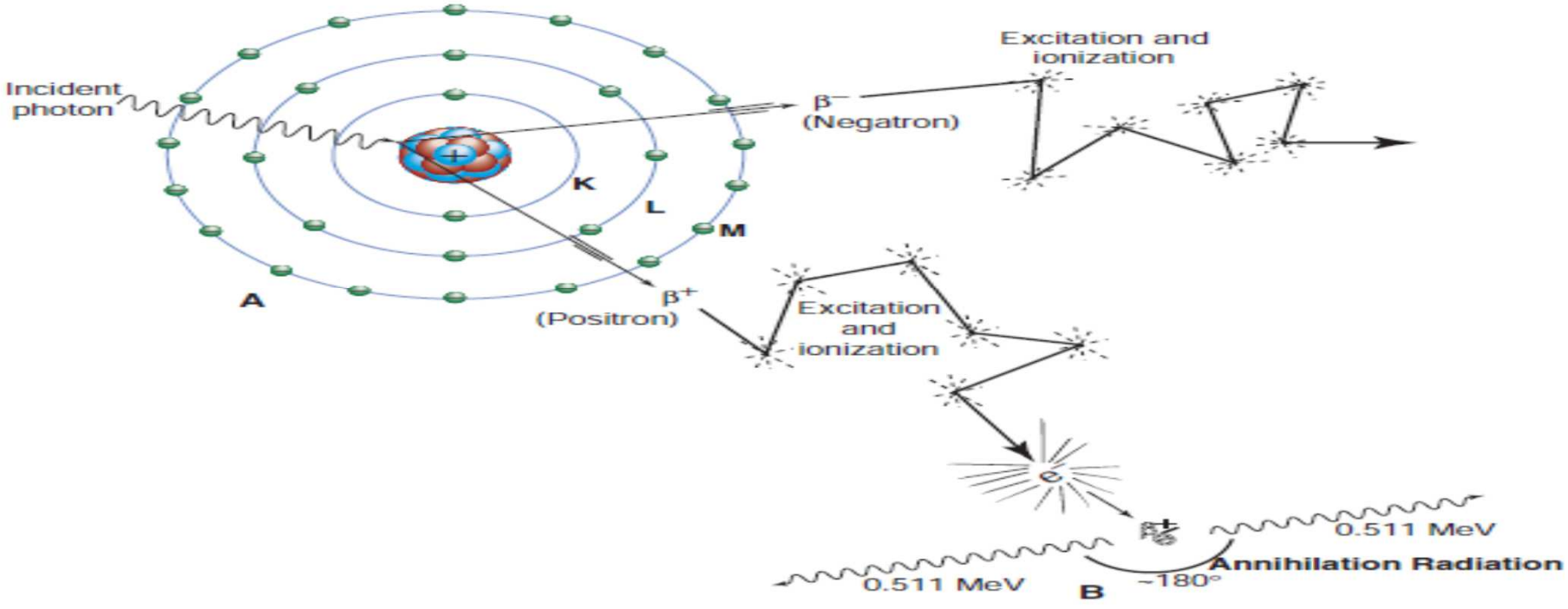
This vacancy will be filled by an electron from a shell with a lower binding energy.

This creates another vacancy, which, in turn, is filled by an electron from an even lower binding energy shell.

Thus, an electron cascade from outer to inner shells occurs.



Pair Production



Pair Production

Pair production can only occur when the energies of x-rays and gamma rays exceed 1.02 MeV.

In pair production, an x-ray or gamma ray interacts with the electric field of the nucleus of an atom. The photon's energy is transformed into an electron-positron pair.

The rest mass energy equivalent of each electron is 0.511 MeV, and this is why the energy threshold for this reaction is 1.02 MeV.

Photon energy in excess of this threshold is imparted to the electron (also referred to as a negatron or beta minus particle) and positron as kinetic energy. The electron and positron lose their kinetic energy via excitation and ionization.

Pair production does not occur in diagnostic x-ray imaging because the threshold photon energy is well beyond even the highest energies used in medical imaging.

Bibliography

1) The Essential Physics of Medical Imaging by Bushberg.
2) Diagnostic Radiology Physics: A Handbook for Teachers and Students by IAEA
3) Radiation Oncology Physics by E.B Podgorsak
4) The Physics of Radiation Therapy by Faiz M. Khan.

About Lecturer:

Opadele A.E is a physics enthusiast with special interest in Medical Physics. He loves to present the complex theories in physics in seemingly simple approach for effectual understanding.

opadelea@babcock.edu.ng

abayomi_opadele

@abayomiopadele

Opadele Abayomi

If you have any questions, let me know