Chapter 20 Medical Physics

Students Learning Outcomes

After studying this chapter, the students will be able to:

- Illustrate how PET scanning works: Positrons emitted by the decay of the tracer annihilate when they interact with electrons in the tissues, producing a pair of gamma-ray photons travelling in opposite directions.
- Explain the piezoelectric effect and its application in medical science: Ultrasound waves are generated and detected by a piezoelectric transducer.
- Explain how ultrasound can be used to obtain diagnostic information about internal body structures.
- Explain that X-rays are produced by electron bombardment of a metal target and calculate the energy.
- Explain the use of X-rays in imaging internal body structures, including a description of the term contrast in X-ray imaging.
- Explain how computed tomography CT-scanning works: It produces a 3D image of an internal structure by first combining multiple X-ray images taken in the same section from different angles to obtain a 2D image of the section, then repeating this process along an axis and combining 2D image of multiple sections.

Medical physics is a branch of physics that applies physical principles and techniques to medicine, especially in the diagnosis and treatment of diseases. It combines knowledge of physics with medical science for the development and use of technologies. This helps doctors to see inside the human body and treat patients safely and effectively. Medical physics plays an important role in modern healthcare technologies by improving the accuracy of medical imaging, reducing radiation risks, and enhancing treatment methods. In our daily life, medical physics is commonly used in hospitals and diagnostic centers through technologies such as X-ray imaging, ultrasound scans, CT-scans, and PET-scans. These techniques allow doctors to detect fractures, diagnose tumors, and to study internal organs without surgery. Thus, medical physics directly contributes to early diagnosis, effective treatment, and improved quality of life. In this chapter, we will learn how advanced imaging techniques are developed using principles of physics. We will study how positron emission tomography (PET) works through positron–electron annihilation and gamma-ray detection. The chapter will also explain the piezoelectric effect and its role in generating and detecting ultrasound waves for medical diagnosis. Furthermore, we will explore the production and use of X-rays.

Introduction to Radiations Used in Medical Physics

Radiation is the transfer of energy through space or matter in the form of waves or particles. In medical physics, radiation is mainly used for diagnosis (imaging) and treatment. Radiation is broadly classified into non-ionizing and ionizing radiation. Ionizing radiation has enough energy to remove electrons from atoms, producing ions. Non-ionizing radiation does not have enough energy to remove electrons from atoms. Examples of radiations used in medical physics are X-rays, gamma rays, and positron. Interaction of X-rays and gamma rays with matter occurs through photoelectric effect and Compton scattering. The positrons are emitted from radioactive tracers. On the other hand, examples of non-ionizing radiations are ultrasound waves and radiowaves. These waves are reflected, refracted, or absorbed when these interact with the matter.

Gamma rays, X-rays, ultrasonic waves, and radiowaves are widely used in medical physics for diagnosis and treatment. X-rays are commonly used to image bones and internal organs, while gamma rays are used in nuclear medicine, such as PET scans and cancer treatment, due to their high penetrating power. Ultrasonic waves are used in ultrasound imaging to examine soft tissues, monitor fetal diseases, and study internal organs safely without ionizing radiation. Radiowaves are used in techniques such as MRI, where they help produce detailed images of internal body structures by interacting with atomic nuclei, making them especially useful for imaging soft tissues without harmful radiation exposure.

20.1 ULTRASOUND AND PIEZOELECTRIC EFFECT

Ultrasound is a widely used, non-invasive medical imaging technique that allows visualization of internal body structures such as tissues, organs, and the fetus during pregnancy. This imaging method operates on a physical principle known as the piezoelectric effect, which is central to the working of an ultrasound transducer. The transducer plays a dual role; it generates ultrasound waves and detects the reflected signals from inside the body.

The Piezoelectric Effect

The word "piezoelectric" comes from the Greek word "piezein," which means "to press", and "electric" refers to the production of electricity.

This effect was discovered in 1880 by two French scientists, Pierre Curie and Jacques Curie. They were experimenting with crystals such as quartz, tourmaline, and Rochelle salt (sodium potassium tartrate). They found that when mechanical pressure was applied to these crystals, they generated an electric charge. Their experiments proved a strong connection between mechanical force and electrical response in certain crystals. The piezoelectric effect is possible because of the unique internal structure of some crystals. There are two types of piezoelectric effect, direct piezoelectric effect and converse piezoelectric effect. These crystals have no

Tidbit!

The piezoelectric effect makes it possible to turn pressure into voltage and vice versa. This is how ultrasound "talks" to the body.

centre of symmetry, and inside them, there are small regions with positive and negative charges. Normally, these charges are balanced, but when pressure is applied, the balance is disturbed, and the charges move slightly, causing an electric field to appear on the surface. This is called the direct piezoelectric effect. On the other hand, if we apply an electric field to the crystal, it changes shape a little. This is called the converse piezoelectric effect. The working of this effect is shown in Fig. 20.1.

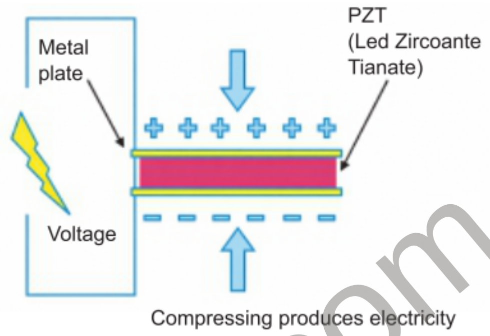

Fig. 20.1: Schematic diagram demonstrating piezoelectric effect

20.2 DIAGNOSTIC USE OF ULTRASOUND IN MEDICAL IMAGING

Ultrasound is a widely used medical imaging technique that allows doctors to view internal body structures in real time. The labelled diagram of ultrasound machine is shown in Fig. 20.2. It operates by sending high frequency sound waves, typically in the range of 1 MHz-15 MHz, into the body using a device called a transducer. These waves travel through the body and reflect off boundaries between different tissues. The reflected echoes are then collected and analyzed to create an image. One of the key advantages of ultrasound is that it does not use ionizing radiation and making it a safe, non-invasive, and repeatable imaging method. The functioning of ultrasound imaging is based on several physical principles. First, the piezoelectric transducer emits pulses of ultrasound waves, which travel at different speeds depending on the type of tissue they pass through. When these waves encounter a boundary between two tissues with different acoustic impedances (determined by tissue density and sound speed), part of the wave is reflected. The transducer then switches to receive mode and detects these

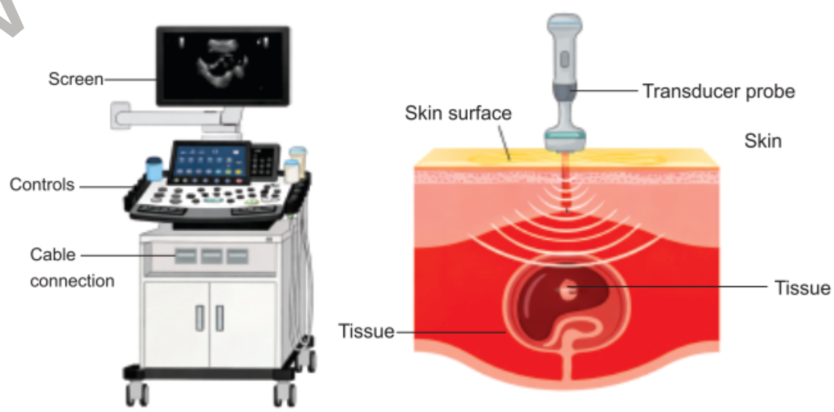

Fig.20.2: Ultrasound machine

reflected waves using the direct piezoelectric effect. These echoes are converted into electrical signals and processed by the machine. Finally, a computer calculates the time delay and intensity of the returning echoes to construct a visual image. Areas with stronger reflections appear brighter in the image, helping to reveal the internal structures of organs and tissues.

Do you know?

The crystals in an ultrasound probe are smaller than a grain of rice, but they can both send and detect sound waves.

Factors Affecting Image Quality

- **Acoustic Impedance Difference:** A higher difference between two tissues (e.g., soft tissue and bone) causes stronger echoes, producing clearer boundaries in the image.
- **Frequency of Ultrasound:** Higher frequency ultrasound offers better resolution but less penetration; lower frequency waves penetrate deeper but have lower image clarity.
- **Use of Gel:** A special gel is applied between the transducer and the skin to remove air gaps and improve sound waves transmission.

Tidbit

Ultrasound can even measure blood flow speed using the Doppler effect detecting shifts in sound frequency.

Applications

Ultrasound imaging is extensively used across various medical specialties for diagnostic purposes. In obstetrics, it helps monitor fetal growth, estimate gestational age, and identify abnormalities during pregnancy. In the abdominal region, ultrasound is used to examine vital organs such as the liver, kidneys, gallbladder, pancreas, and bladder. In cardiology, echo cardiography allows doctors to evaluate the heart's structure and function in real time. The field of urology also benefits from ultrasound for examining the prostate, testicles, and urinary system. Additionally, in the musculoskeletal system, it aids in detecting ligament injuries, joint inflammation, and other soft tissue conditions.

20.3 X-RAYS

The transitions of electrons in the hydrogen or other light elements result in the emission of spectral lines in the infrared, visible or ultraviolet region of electromagnetic spectrum due to small energy differences in the transition levels.

In heavy atoms, the electrons are assumed to be arranged in concentric shells labelled as K, L, M, N, O, etc. The K-shell being closest to the nucleus, the L-shell next, and so on (Fig. 20.3). The inner shell electrons are tightly bound and large amount of energy is required for their displacement from their normal energy levels. After excitation, when an atom returns to its normal state, photons of larger energy are emitted. Thus transition of

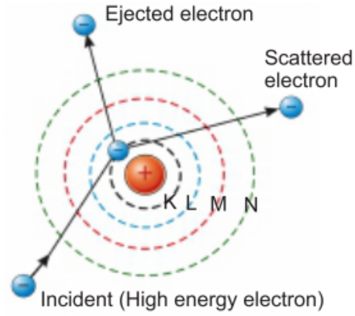

Fig. 20.3: Concentric energy shells

inner shell electrons in heavy atoms gives rise to the emission of high energy photons or X-rays. These X-rays consist of series of specific wavelengths or frequencies and hence are called characteristic X-rays. The study of characteristic X-rays spectra has played a very important role in the study of atomic structure and the periodic table of elements (Fig. 20.4).

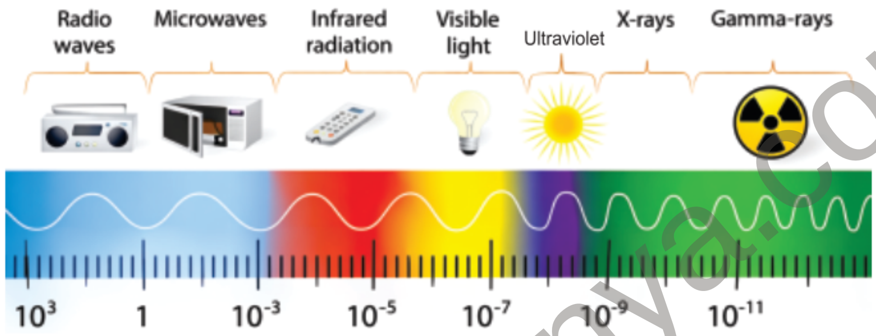

Fig. 20.4: Electromagnetic spectrum

Production of X-rays

Fig. 20.5 shows an arrangement of producing X-rays. It consists of a high vacuum tube called X-ray tube. When the cathode is heated by the filament F. it emits electrons which are accelerated towards the anode T. If *V* is the potential difference between C and T, the $(K.E.)_{max}$ with which the electron strikes the target is given by

$$(K.E.)_{max} = Ve \quad \ldots\ldots\ldots\ldots\ldots (20.1)$$

Suppose that these fast moving electrons of energy *Ve* strike a target made of tungsten or any other heavy element. It is possible that in collision, the electrons in the innermost shells, such as K or L, will be knocked out. Suppose that one of the electrons in the K-shell is removed, thereby producing a vacancy or hole in that shell. The electron from the L-shell jumps to occupy the hole in the K-shell, thereby emitting a photon of energy

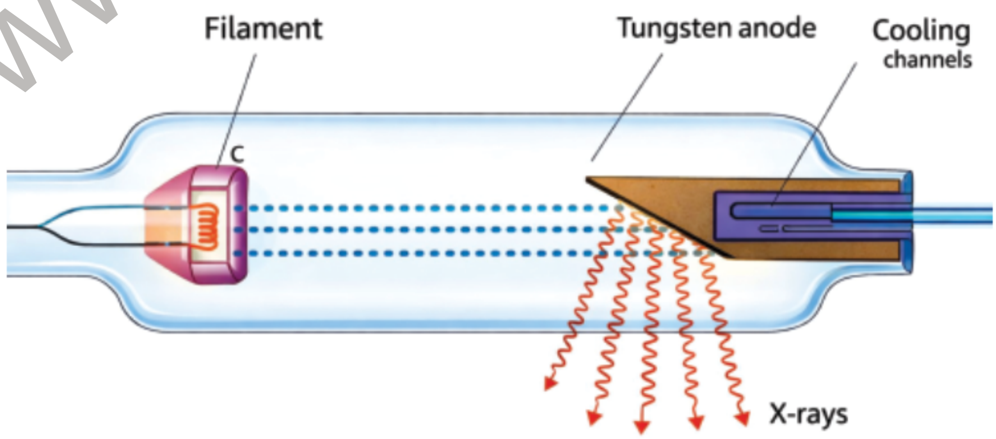

Fig. 20.5: Arrangement for producing X-rays

hf_1, called the K_α X-ray given by

$$hf_{K_\alpha} = E_L - E_K \text{ .... } (20.2)$$

It is also possible that the electron from the M-shell might also jump to occupy the hole in the K-shell. The photons emitted are K_β X-ray with energies these photons give rise to K_β X-ray and so on.

$$h\,f_{K_\beta} = E_M - E_K \text{ .... } (20.3)$$

The photons emitted in such transitions i.e., inner shell transitions are called characteristic X-rays, because their energies depend upon the type of target material.

The holes created in the L and M shells are occupied by transitions of electrons from higher states creating more X-rays. The characteristic X-rays appear as discrete lines on a continuous spectrum as shown in Fig. 20.6.

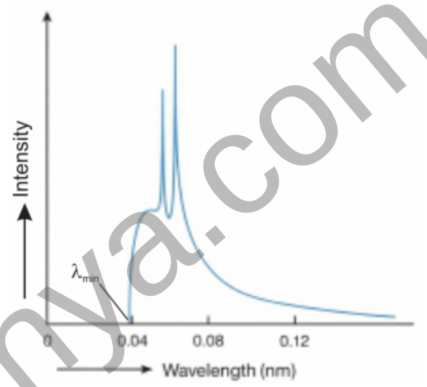

Fig. 20.6

The Continuous X-ray Spectrum

The continuous spectrum is due to an effect known as bremsstrahlung or braking radiation. When the fast moving electrons bombard the target, they are suddenly slowed down on impact with the target. We know that an accelerating charge emits electromagnetic radiation. Hence, these impacting electrons emit radiation as they are strongly decelerated by the target. Since the rate of deceleration is so large, the emitted radiation correspond to short wavelength and so the bremsstrahlung is in the X-ray region. In the case when the electrons lose all their kinetic energy in the first collision, the entire kinetic energy appears as a X-ray photon of energy hf_{max} i.e.,

$$(K.E.)max = h\,f_{max}$$

The wavelength λ_{min} in Fig. 20.6 corresponds to frequency f_{max}. Other electrons do not lose all their energy in the first collision. They may suffer a number of collisions before coming to rest. This will give rise to photons of smaller energy or X-rays of longer wavelength. Thus the continuous spectrum is obtained due to deceleration of impacting electrons.

X-Ray Imaging

As X-rays travel through the body, they lose energy because they interact with atoms. This process is called attenuation. X-rays can ionize atoms; it means that they knock out electrons which is how energy is transferred. The intensity of the X-ray beam decreases gradually as it passes through a material. This drop follows an exponential pattern. The formula for this is:

$$I = I_o\, xe^{(-\mu x)}$$

where I_o = Initial intensity

I = intensity after passing through material

x = thickness of the material (in metres)

μ = attenuation coefficient (depends on the material and X-ray energy)

Image intensifiers are used in real-time X-ray imaging (fluoroscopy). They help reduce radiation exposure by brightening the image, making it easier to see. Contrast in X-ray images means how clearly, we can tell different tissues apart. Contrast depends on x-rays energy. Hard X-rays (high energy) are used for bone imaging. Soft X-rays (low energy) are better for soft tissues like the breast. Contrast media are basically special substances like iodine (Z = 53) or barium (Z = 56) that absorb X-rays well. They are injected or swallowed to highlight certain parts of the body. Since they have high atomic numbers, they increase X-ray absorption and make tissues stand out more clearly.

20.4 COMPUTED TOMOGRAPHY SCANNING (CT-SCAN)

Computed Tomography, commonly known as CT-Scan, is a medical imaging technique that combines X-ray technology with computer processing to generate high-resolution cross-sectional and 3D images of internal body structures. It is especially useful for diagnosing diseases, detecting internal injuries, and guiding medical treatment. An ordinary X-ray shows a flat (2D) image of the body, where different parts like bones and organs overlap each other. This makes it hard to see individual structures clearly. For example, in Fig. 20.7, it's difficult to tell the front and back ribs apart because they appear on top of each other. To solve this problem, doctors use a special technique called CT scan (Computed Tomography).

Fig. 20.7

A CT scanner takes many X-ray images of the same body section from different angles. A computer combines these images to make a detailed cross-sectional (slice) image of the body. Then, the scanner moves slightly along the body and repeats the process for the next slice. In the end, all these slices are combined by the computer to create a 3D image of the internal structure.

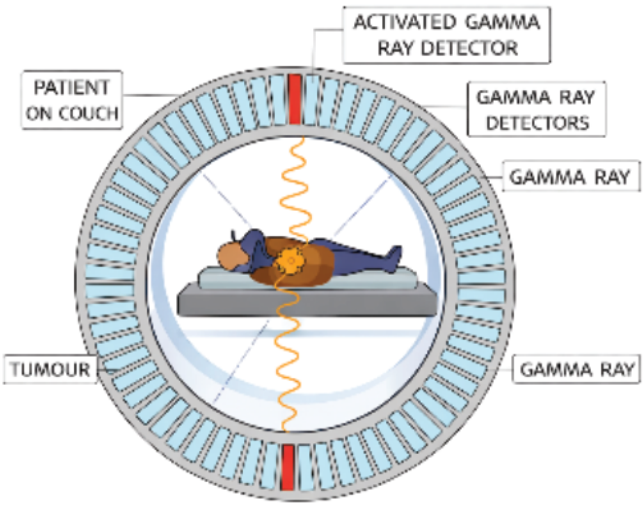

Fig. 20.8: Operation of CT-scanner

In a CT machine, the X-ray tube rotates around the patient while detectors stay in place. This setup collects complete information from all sides, as shown in Fig. 20.8.

The name computed tomography comes from:

- **Computed:** A computer processes the data.
- **Tomography:** From the Greek word *tomos*, meaning **slice.**
- **Axial:** The scan is taken along the body's axis (line through the body).

Do you know?

The CT-scanner was invented by Sir Godfrey Hounsfield (England) and Allan Cormack (South Africa) in the early 1970s. For this invention, both scientists were awarded the Nobel Prize in Physiology or Medicine in 1979.

Fig. 20.9: A boy undergoing a CT scan; monitor shows head cross-section.

Do you know?

CT-scans create hundreds of slices are images in seconds like peeling a digital apple layer by layer. CT-scans can detect strokes within minutes of onset crucial for lifesaving treatment.

This way, doctors can get a clear and detailed view of internal organs, bones, or tissues. Fig. 20.9 shows a child having a CT scan, and the monitor displays a cross-sectional image of the head. This technique is called Computed Axial Tomography (CT scan) because it uses a computer to control the scanning process, collect data, and convert it into images. The X-ray tube rotates around the patient's body, capturing images from different angles. These images are then used to create detailed cross-sectional slices of the body. The word “tomography” comes from the Greek word tomos, meaning “slice,” which refers to how the body is imaged layer by layer.

Advantages of CT-Scan

CT scans offer several important advantages over traditional X-rays. While single X-ray images are still useful and quick to produce, they only give a flat, two-dimensional view. In contrast, CT scans produce three-dimensional images, allowing doctors to see the size, shape, and exact location of organs, bones, and other structures inside the body. This makes it easier to distinguish between tissues, even when they have very similar densities. For example, a CT scan can clearly show the position and size of a tumor, which helps doctors accurately target it during treatment using high-energy X-rays or gamma rays. However, it is important to remember that CT scans involve exposure to X-rays, which are a form of ionizing radiation. Although the amount of radiation is relatively low, it still carries a small risk to the patient. On average, the radiation dose from a CT evaluating brain function, and identifying cardiac abnormalities before clear anatomical changes appear (Fig. 20.10).

Working of PET SCAN

A schematic diagram of PET scanning machine is shown in Fig. 20.11. In the PET scan, a small amount of radioactive tracer is injected into a vein. The tracer is carried by the blood and builds up more in tissues that are very active, such as many cancers or working parts of the brain and heart. As the unstable nuclei of the tracer decay, they emit positrons. Each positron travels only a short distance before meeting an electron in nearby tissue. When they meet, the positron and electron annihilate and their mass is converted into energy in the form of two gamma-ray photons that move in opposite directions. Detectors arranged in a ring around the patient detect these photon pairs and send the signals to a computer, which constructs clear images showing where the tracer has collected. Brighter areas on the PET image correspond to regions of higher tracer concentration and therefore higher tissue activity.

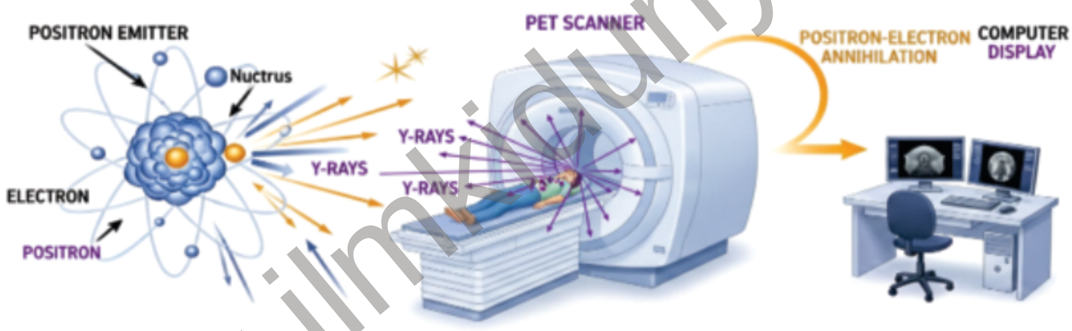

Fig. 20.11: Schematic diagram of PET-scanning

Medical Physics in Cancer treatment

Medical physics is also of great importance in the treatment and diagnosis of cancer especially through radiotherapy which makes use of high energy particles to kill tumor cells with minimal harm to other healthy tissues. Radiation therapy can be done by using two main approaches, one of which is through teletherapy in which radiation is delivered externally from a machine positioned outside the body, and another approach is through brachytherapy whereby a radioactive source is inserted inside or close to the tumor.

Medical physicists are also part of oncology team and they specialize in equipment quality assurance, calculation of time of treatment, planning of treatment as well as mapping dose distribution throughout the cancerous region. They work hand in hand with radiation oncologists, dosimetrists, and laboratory technicians in ensuring every treatment is safe and clinically effective

QUESTIONS

Multiple Choice Questions

Choose the correct answer.

20.1 What kind of radiation is detected in a PET scan after positron annihilation?
(a) Beta particle (b) Gamma rays (c) X-rays (d) Alpha particles

20.2 What is the role of coincidence detection in PET-scanning?
(a) To control the temperature of the scanner
(b) To detect gamma rays arriving simultaneously
(c) To block unwanted radiation
(d) To generate X-rays

20.3 Which principle allows ultrasound transducers to emit and detect sound waves?
(a) Piezoelectric effect (b) Doppler effect
(c) Photoelectric effect (d) Thermoelectric effect

20.4 Which body part is commonly examined using ultrasound imaging?
(a) Skull (b) Bones (c) Abdomen (d) Teeth

20.5 In X-ray imaging, what does "contrast" mainly depend on?
(a) Density and thickness of tissues (b) Heartbeat rate
(c) Distance from the detector (d) Surface temperature of the body

20.6 What advantage does a CT scan have over a standard X-ray image?
(a) Less radiation exposure (b) Simpler equipment
(c) Produces 3D images from 2D slices (d) Uses sound waves instead of X-rays

20.7 What kind of wave is used in ultrasound imaging?
(a) Longitudinal sound wave (b) Transverse sound wave
(c) Electromagnetic wave (d) Ionizing radiation wave

20.8 Characteristic X-rays are produced due to:
(a) nuclear reactions (b) inner shell electronic transitions
(c) outer shell transitions (d) ion collisions

20.9 What does CT stand for in medical imaging?
(a) Combined Tomography b) Computed Telemetry
(c) Computed Tomography (d) Centralized Therapy

Short Answer Questions

20.1 Which type of radiation is produced during a PET scan?
20.2 Which physical effect enables ultrasound transducers to produce sound waves?

20.3 Mention one area of the body commonly examined using ultrasound.

20.4 What causes contrast in X-ray images of different body tissues?

20.5 State one major difference between a CT scan and a standard X-ray image.

20.6 What occurs when ultrasound hits the boundary between two tissues?

20.7 What does the abbreviation "CT" stand for, and how does it improve imaging?

20.8 What do you know about the terms k_α, k_β, k_p, X-rays.

Constructed Response Questions

20.1 What does a time difference in detecting gamma rays at two detectors indicate in a PET scan?

20.2 Why is ultrasound not effective for imaging air-filled organs like the lungs?

20.3 What happens when the X-ray contrast between two tissues is too low? Suggest a solution.

20.4 How does CT scanning reduce the overlapping of organs seen in plain X-rays?

20.5 What could be a possible medical cause of uneven tracer concentration seen in a PET brain scan?

20.6 What is the purpose of lead collimators in PET gamma-ray detectors?

Comprehensive Questions

20.1 What is the piezoelectric effect, and how does it allow transducers to both emit and detect ultrasound waves?

20.2 Describe how an ultrasound image is created using the concepts of echoes and reflected sound waves.

20.3 Explain how the absorption (attenuation) of X-rays by different tissues creates contrast in the resulting image. Include an example.

20.4 Compare CT and conventional X-ray imaging with respect to image clarity and diagnostic value.

20.5 Define tomography and explain how CT scanning creates 3D images using 2D slices.

20.6 How would you explain the inner shell transitions of X-rays? Also explain characteristic and continues X-rays.

Numerical Problems

20.1 An electron jumps from a level $E_i = -3.5 \times 10^{-19}$ J to $E_f = -1.20 \times 10^{-18}$ J. What is the wavelength of the emitted light? (**Ans:** 234 nm)

20.2 Electrons in an X-ray tube are accelerated through a potential difference of 3000 V. If these electrons were slowed down in a target, what will be the minimum wavelength of X-rays produced? (**Ans:** 4.14×10^{-10} m)

20.3 The wavelength of K X-ray from copper is 1.377×10^{-10} m. What is the energy difference between the two levels from which this transition results?

(**Ans:** 9.03 KeV)

20.4 A tungsten target is struck by electrons that have been accelerated from rest through 40 kV potential difference. Find the shortest wavelength of the bremsstrahlung radiation emitted. (**Ans:** 0.31×10^{-10} m)

Chapter 21

Space and Environment

Students Learning Outcomes

After studying this chapter, the students will be able to:

- Explain the term luminosity [as the total power of radiation emitted by a star]
- Apply the inverse square law for radiant flux intensity [*F* in terms of the luminosity *L* of the source $= \frac{L}{4\pi r^2}$.
- Define and apply standard candles [Explain the use of standard candles to determine distances to galaxies]
- Explain blackbody radiation and apply Wien's displacement law to solve problems [$\lambda_{max} T$ = constant to estimate the peak surface temperature of a star]
- Apply the Stefan-Boltzmann law [$L = 4\pi r^2 \times \sigma T^4$ to solve problems]
- Estimate the radius of a star [applying Wien's displacement law and the Stefan-Boltzmann law]
- Explain that the lines in the emission and absorption spectra from distant objects show an increase in wavelength from their known values
- Explain why redshift leads to the idea that the Universe is expanding [include using $\frac{\Delta \ell}{\ell} \approx \frac{\Delta f}{f} \approx \frac{v}{c}$ for the redshift of electromagnetic radiation from a source moving relative to an observer to solve problems relating to the expanding universe]
- State and explain Hubble's law and how it leads to the Big Bang theory
- Describe Earth's climate system as a complex system having five interacting components [the atmosphere (air), the hydrosphere (water), the cryosphere (ice and permafrost), the lithosphere (earth's upper rocky layer) and the biosphere (living things).]
- Relate ocean currents and wind patterns to the climate system
- Explain how global climate is determined by energy transfer from the Sun [with specific reference to the below factors and terms: state and use the term Earth energy budget Explain how the energy imbalance between the poles and the equator can affect atmospheric circulation]
- Explain that due to the conservation of angular momentum, the Earth's rotation diverts the air to the right in the Northern Hemisphere and to the left in the Southern hemisphere, thus forming distinct atmospheric cells.
- Explain that ocean water that has more salt has a higher density and differences in density play an important role in ocean circulation.
- Explain how the thermohaline circulation transports heat from the tropics to the Polar Regions.

Space and environment are two important and closely related fields that help us to understand both the universe and our planet. Space refers to a region beyond Earth's atmosphere in which all celestial bodies, such as planets, stars, and galaxies, exist and interact through gravity and electromagnetic radiations. Environment is the surrounding physical, chemical, and biological conditions in which living and non-living systems exist and interact. It includes air, water, land, climate, ecosystems, and all