LECTURE 1: ELECTROMAGNETIC RADIATION

1.0 -- PURPOSE OF UNIT

The purpose of this unit is to identify and describe some of the basic properties common to all forms of electromagnetic radiation and to identify x-rays and gamma rays as a form of electromagnetic radiation.

1.1 -- INTRODUCTION

Many procedures in the diagnosis and treatment of malignant disease involve the use of electromagnetic radiation. For example, patient R. S., who came to the radiation oncology clinic for treatment of a lung tumor, had his tumor first identified by means of a chest radiograph. When the chest radiograph was taken, electromagnetic radiation was made to pass through his body and the differences in absorption of the radiation were recorded on film and correlated with anatomic structures and pathologies. By observing the image of R.S.'s lung, his physician was able to correlate a specific area with the suspicion of a malignant tumor. Once the suspicious area was identified as a tumor, R.S. had to undergo a bone scan. In this nuclear medicine imaging procedure, a radioactive material is incorporated into tissue. The electromagnetic radiation emitted by the material is measured and its position correlated to areas of increased uptake of the radioactive material. These areas of increased uptake in R.S.'s bone scan would have indicated the possible presence of metastatic disease. In the case of a patient treated for breast cancer, the technique of computed tomography proved an effective tool for tumor localization. In this procedure electromagnetic radiation passed through the patient and its intensity was measured. The differences in absorption of the radiation were calculated and the information processed through a series of computations to give a detailed distribution of absorption in a transverse plane of the patient. Endoscopy may also be used in tumor diagnosis. This procedure also involves electromagnetic radiation. In this case the reflection of light waves is used to identify lesions. Electromagnetic radiation is also used for therapeutic purposes, to kill
tumor cells and control malignant growth. In fact, the entire objective of radiation therapy is to control malignancies by means of the controlled use of high-energy electromagnetic radiation.

In order to understand the mechanisms by which electromagnetic radiation is used for both the diagnosis and the treatment of malignant disease, it is necessary to have some understanding of the nature of electromagnetic radiation. Moreover, knowledge of the nature of electromagnetic radiation is also crucial to understand some of the limitations of the various techniques of diagnosis and therapy. The purpose of this unit is to introduce the study of electromagnetic radiation by identifying and describing some of the basic properties common to all forms of electromagnetic radiation.

In later units we shall focus our attention on the particular type of electromagnetic radiation used in radiation therapy, that is, ionizing radiation. We will first identify and locate ionizing radiation in the hierarchy of radiations. We will then describe its dual nature as either waves or as particles. The unit will conclude with a discussion of the various properties that characterize radiation as either wavelike or as particlelike.

1.2 -- THE HIERARCHY OF RADIATION

First, let us identify a hierarchy in the study of radiation. Radiation itself describes any type of transfer of energy by means of waves. Electromagnetic radiation is included among the types of radiation, but other types of radiation also exist. For example, a common type of radiation used in medical diagnosis is comprised of high frequency pressure waves in a medium. These waves, of course, are sound waves, and the sound waves in the high frequency regime used for imaging are referred to as diagnostic ultrasound. Electromagnetic radiation is the radiation that is produced by the motion of electric charges. There are many types of electromagnetic radiation. One type has sufficient energy to remove electrons from atoms, that is, to ionize the atoms. This type is called ionizing radiation and it is the type referred to when we speak of the radiation used in diagnostic or therapeutic radiology. X-rays and gamma rays are the two types of ionizing
radiations we use most frequently. Thus, the hierarchy starts out with radiation, which has electromagnetic radiation as a subcategory. Electromagnetic radiation in turn has a subcategory known as ionizing radiation. In this unit we shall be discussing properties of electromagnetic radiation in general, and in later units we shall look at the specific properties of ionizing radiation, in particular, those properties that make ionizing radiation useful for the treatment of malignant disease.

1.3 -- THE DUAL NATURE OF IONIZING RADIATION

One very important property of electromagnetic radiation is an unusual one, and perhaps a seemingly contradictory one. Electromagnetic radiation can be described either as waves or as particles. That is, electromagnetic radiation may exhibit either wavelike properties or particlelike properties. Moreover, whether it has wavelike properties or whether it has particlelike properties will depend only on which properties you are looking for. If you want electromagnetic radiation to behave as a wave, and you perform an experiment to measure wave properties, it will exhibit wavelike properties. On the other hand, if you prefer that it behave as a particle, it will oblige by exhibiting particlelike properties. It will never, however, exhibit both sets of properties at the same time.

1.3.1 -- WAVE PROPERTIES OF IONIZING RADIATION

What are some of these specific wavelike and particlelike properties which electromagnetic radiation exhibits? We shall look at each set of properties, wavelike and particlelike, in turn. The first class of properties we shall examine are the wavelike properties of electromagnetic radiation. First, it is necessary to identify what is meant by a wave. A wave can be defined as a periodic disturbance that can be transmitted, or propagated, from one point to another point. The word “periodic” means that this disturbance repeats itself regularly. Two directions can be identified in this definition of a wave, the direction of the disturbance and the direction of propagation. The relationship between these two directions will classify waves into two
categories. If the disturbance moves in the same direction as the propagation, the waves are called longitudinal. A good example of a longitudinal wave is a sound wave. If the disturbance moves perpendicular to the direction of propagation, the waves are called transverse. An example of a transverse wave is an electromagnetic wave.

One can get a good illustration of the types of waves by playing with a “Slinky”, a loosely coiled spring that has been a popular children's toy. Ask a colleague to take one end of the Slinky, while you take the other end and stretch it out. Now grab a few coils, compress them, and let them go. The disturbance will travel down the Slinky to your friend and back again to you. Both the disturbance and the propagation are horizontal; thus the wave produced is a longitudinal wave. Now, move the end of the Slinky up and down. Again, a wave is produced as the up and down disturbance moves to your friend and back again. In this case, however, the disturbance is vertical while the direction of propagation is still horizontal. Now we are observing a transverse wave. Observe that in neither case does the spring itself actually move from you to your friend, or back again. It is only the disturbance that is propagated along the length of the spring.

The two important quantities that describe the motion of a wave are the amplitude and the frequency of the wave. The amplitude is defined as the magnitude of the disturbance, while the frequency is defined as the number of disturbances per unit time. The frequency is denoted by the Greek letter \( \nu \). Its unit is the Hertz (Hz), which is equal to one cycle per second. Waves can also be described by a related quantity, the wavelength, defined as the distance between successive peaks. The wavelength is denoted by the Greek letter \( \lambda \). Its units are units of length such as the meter. Wavelength and frequency are not independent of one another; they are related by the equation.

\[
\lambda \nu = c,
\]

where \( c \) is the speed at which the disturbance is propagated.
A good analogy of the relationship between wavelength, frequency, and speed can be observed in a moving railroad train. The distance from the front of one car to the front of the next car in the train can be compared to the wavelength, the distance between corresponding points on adjacent cars. The number of cars that pass a given fixed point in a given time interval is the frequency. If you multiply the train’s “wavelength” by its “frequency,” the result is the speed at which the train is traveling. This exercise would be a good one to do the next time you find yourself sitting in an automobile stopped at a railroad crossing as one of those interminably long freight trains rolls by.

**Problem:** Suppose you are waiting at a railroad crossing while a train is passing by. You take out your stopwatch and find that 60 cars pass by the railroad crossing every minute. If the length of a car is 75 feet, how fast is the train moving?

**Solution:**

\[
\text{speed} = \text{wavelength} \times \text{frequency} \\
= 75 \text{ ft/car} \times 60 \text{ cars/min} \\
= \frac{4500 \text{ ft/min} \times 60 \text{ min/hr}}{5280 \text{ ft/mile}} \\
= 51 \text{ miles/hr}
\]

Doing this type of calculation may make the waiting time seem somewhat shorter.

The class of waves known as electromagnetic waves, which have such importance in medical diagnosis and therapy, are transverse fluctuations in electric and magnetic fields caused by interactions of charged particles. Since they are transverse waves, the motion of the disturbances is perpendicular to the motion of propagation. This direction of the motion of the disturbances is called the polarization of the wave. Electromagnetic waves may have wavelengths ranging from many meters down to lengths as short as \(1.0 \times 10^{-12}\) meter, or even smaller. Table 1.1 lists some of the most familiar types of electromagnetic waves as well as their approximate wavelengths.
In addition to the fact that they are all fluctuations in electric and magnetic fields, electromagnetic waves have another major property in common: they all travel at the same speed in a vacuum. That speed, also representing the fastest speed at which anything may travel, is $3.00 \times 10^8$ m/sec. This speed is commonly referred to as “the speed of light”.

**Problem:** Radio station KXRA broadcasts at a frequency of 810 kHz. What is its wavelength?

**Solution:**

$$\lambda = \frac{c}{v} = \frac{3.00 \times 10^8 \text{ m/sec}}{8.10 \times 10^7 \text{ cycles/sec}} = 370 \text{ m.}$$

Although electromagnetic waves are most commonly thought of in terms of their wave properties, the quantum theory states that electromagnetic waves may exhibit either wave properties or particle properties. It is important to recognize the existence of this duality because certain phenomena involving electromagnetic waves can only be explained if they are
viewed as waves, while other phenomena can only be explained if electromagnetic waves are treated as particles. This duality is one of the key principles of the quantum theory.

Phenomena associated with electromagnetic radiation, which are characteristic of waves, include diffraction and interference. Diffraction is the ability of a wave to bend around a corner. For example, if you stand near the corner of a building, you will still hear sounds produced around the corner of the building, although the building stands between you and the source of the sound wave. You cannot see the source because light waves are not diffracted as much around the building corner as the sound waves. Thus, we also observe that the extent of a particular wave phenomenon is very much dependent on the properties of the wave.

Interference, the other phenomenon associated with waves, occurs when two waves are combined. Waves may combine either constructively, in which an amplitude peak of one wave is added to an amplitude peak of another wave, or destructively, in which an amplitude peak is added to an amplitude trough. If the two waves are of equal amplitudes, then constructive interference gives a resulting wave with amplitude twice the original wave, while when destructive interference occurs, the waves cancel each other out. Figure 1.1 shows the effects of constructive and destructive interference in the addition of two waves.

![Figure 1.1](image.png)

**Figure 1.1:** Constructive interference causes intensity maxima to occur at $R_0$ and $R_1$, while destructive interference causes minima to occur at $I_1$.

A good example of interference occurs when electromagnetic waves are diffracted from two nearby structures. Figure 1.1 illustrates one example of interference, light waves passing...
through a pair of slits, while Figure 1.2 shows another example of interference, x-rays diffracted from two atoms. For the phenomenon of interference to occur, the separation of the adjacent structures, in these cases, the slits or atoms, must be approximately equal to the wavelength of the incident wave. X-rays have a wavelength of approximately 0.1 Å (1 Å = 1.0 × 10⁻⁸ cm), so that interference will occur only if the structures are in the vicinity of 0.1 Å in size. While atoms in a crystal have spacings of approximately several Å, and thus can give rise to interference, structures involved in medical situations are considerably larger, thus interference is not as significant in applications in clinical medicine.

Figure 1.2: X-rays diffracted from adjacent atoms give rise to interference patterns similar to those observed from light diffracted from slits.

In cases when typical dimensions are many times greater than the wavelength of the electromagnetic radiation, the particle properties of the radiation become much significant. We can view electromagnetic waves as discrete clumps, or quanta, of energy. These quanta can be envisioned as particles of energy called photons. Photons are massless particles which travel at the same speed as electromagnetic radiation, or 3.00 × 10⁸ m/sec. Each photon contains an amount of energy related to the wavelength of the radiation, according to the equation

\[ E(\text{keV}) = \frac{12.4}{\lambda(\text{Å})}. \]  

**Problem:** Red light has a wavelength of approximately 7000 Å. What is its energy?
Solution:

\[
E(\text{keV}) = \frac{12.4}{\lambda(\text{A})} = \frac{12.4}{7000} = 0.00177 \text{ keV} = 1.77 \text{ eV}.
\]

One may also use equation (1.2) to find \( \lambda \) given \( E \).

Problem: What is the wavelength of 62 keV x-rays?

Solution:

\[
\lambda(\text{A}) = \frac{12.4}{E(\text{keV})} = \frac{12.4}{62} = 0.2 \text{ A}
\]

1.3.2 -- PARTICLE PROPERTIES OF ELECTROMAGNETIC RADIATION

Electromagnetic radiation can also exhibit particle properties. A good example of a situation in which electromagnetic radiation exhibits such particle properties can be found by observing the photoelectric effect. One such instance occurs when we shine light on a photocell and cause a current to flow. It is possible to design a photocell such that it will operate if white or blue light is shone on it but not when exposed only to red light. Red light will not activate the photocell no matter how intense the light is, but a very faint white or blue light will activate the cell. The explanation for this is straightforward only if we make the assumption that the light consists of a beam of particles whose energy is inversely proportional to their wavelength. Blue light has a shorter wavelength than red light, so blue light particles have higher energy than red light particles. Current in the photocell will flow only if the energy of an incident light particle is higher.
than a certain value. In this example, the energy of a red light particle is not high enough to cause current to flow while the energy of the blue light particles is sufficiently high. White light includes both blue and red light, so it is the blue light particles in the white light that activate the photocell. The term given to these light particles is “photon”. Thus, a beam of light can be viewed in this model as a beam of photons.

The final question that must be asked is “When does electromagnetic radiation behave like waves and when does it behave like particles?” The answer is simple: you get what you are looking for. If you design an experiment to measure the wavelike properties of electromagnetic radiation, then it will behave as a wave. If the experiment is designed to measure particle properties, then the electromagnetic radiation will behave as particles. The important point to note is that in a single measurement, electromagnetic radiation will behave as either waves or particles, but never as both simultaneously.