Chapter 30
X Rays

GOALS

When you have mastered the material in this chapter, you will be able to:

Definitions
Define each of the following terms, and use it in an operational definition:

- hard and soft x rays
- Bremsstrahlung
- characteristic x rays
- absorption coefficient
- Roentgen
- rad
- rem
- reb; RBE

X-ray Problems
Solve problems involving the generation, absorption, and detection of x rays.

X-ray Interactions
List and discuss the interactions of x rays with matter—particularly those with humans.

PREREQUISITES

Chapter 30

X Rays

30.1 Introduction

What are the characteristics of x rays that make them useful in medical diagnosis and therapy? How is it possible for some color television sets to generate x rays? If you cannot see x rays, how can they be detected? X rays are electromagnetic radiation with wavelengths of the order of $10^{-10}$ m. This corresponds to photon energies in the kiloelectron volt region. In this chapter you will be introduced to the physical basis of x-ray generation and detection. You will study the characteristics of x rays and their interaction with matter. Your understanding of the physical basis of x-ray phenomena will enable you to understand the value of x rays in the health sciences.

30.2 X Rays

Wilhelm K. Roentgen, who in 1901 was the first man to receive the Nobel Prize in physics, first observed x rays in 1895. He was studying the light produced when electricity was passed through a gas in a tube at low pressure. He noted that a paper screen coated with a fluorescent material glowed when it was in the vicinity of the tube under operation. We now know that x rays are produced if electrons are accelerated through a potential of the order of $10^4$ or more volts and then allowed to strike a metal target. Classical electromagnetic theory indicates that the deceleration of an electric charge causes it to radiate energy. In this case the form of electromagnetic radiation is called x rays. Early observations showed that this newly detected radiation had greater penetration power than any other electromagnetic radiation known at that time. It was also observed that these x rays affected a photographic film and would ionize atoms. These effects are utilized in detecting devices for x rays. Since x rays are electromagnetic waves, they are not deflected by either an electric or a magnetic field.

The usual way of producing x rays involves the use of the thermionic x-ray tube as shown in Figure 30.1.

**FIGURE 30.1**
Diagram of an x-ray tube. The heated filament emits electrons, which are accelerated through a potential of more than 10,000 V. The electrons strike the anode and cause it to emit energy as x-ray photons. The anode serves as a transducer changing the kinetic energy of the electrons into heat energy and electromagnetic radiation energy in the x-ray region of the spectrum.
The heated filament supplies electrons that are accelerated through a large potential difference (generally of the order 104 and 105 volts) between the cathode and the anode. The electron beam is focused by the use of electric fields onto the anode. The wavelength of the x rays is controlled by the applied voltage between the cathode and anode. For the higher potential differences (short wavelengths) the term hard x rays is used and for the lower potential differences (long wavelengths) the term soft x rays is used to describe the quality of the radiation. Since the tube is highly evacuated, the electron beam current (usually in the 10 milliampere range) is determined by the filament current. When these electrons strike the metal anode target some of them generate x rays as they are abruptly brought to rest. This deceleration radiation is called Bremsstrahlung (braking radiation) which appears as the continuous x-ray background shown in Figure 30.2.

FIGURE 30.2
A typical x-ray spectrum with the intensity $I$ of the x rays in arbitrary units plotted against the wavelength $\lambda$ of the x rays. From the Planck relationship ($E = h\nu/\lambda$), note that the highest-energy x rays are those with low wavelengths. The Bremsstrahlung x-ray radiation forms the smooth continuous spectra. The sharp peaks are the characteristic x-ray spectral lines. These lines are characteristic of the kind of metal used as a target. This figure represents an emission spectrum of tungsten. The value of $\lambda_{\text{min}}$ is given by $hc/(\text{voltage})e$, where $e$ is the charge on an electron.

Much of the electron energy goes into heating up the anode. Some of the electrons in the beam interact with the innermost, most tightly, bound electrons in the target and "knock" them into excited states. When these excited atoms return to their ground state, photons are emitted. Since the target material is a metal with many electrons, the innermost electron energy levels are of the order of thousands of electron volts (keV). The photons emitted due to this excitation are characteristic of the target material and are called the characteristic spectra.

The maximum energy x rays correspond to the conversion of the maximum electron beam energy into a photon,

$$eV = hf_{\text{max}} = \frac{hc}{\lambda_{\text{min}}} \quad (30.1)$$

where $V$ is the accelerating voltage for the tube, $f_{\text{max}}$ is maximum x-ray frequency, $h$ is Planck's constant, and $e$ is the change of the electron.
EXAMPLE

An x-ray tube is operated at a potential of 62,000 V. Find the short wavelength limit of the x rays emitted.

\[ hf_{\text{max}} = \frac{hc}{\lambda_{\text{min}}} = eV = 62 \text{ keV} \]

\[ \lambda (\text{nm}) = \frac{1240 \text{ eV-nm}}{62,000 \text{ eV}} = 0.02 \text{ nm} \]

where \( \frac{hc}{e} \) = constant = 1240 eV-nm (to three significant figures). This is a good number to remember for quick conversion of wavelengths and voltages. That is,

\[ \lambda V = 1240 \text{ eV-nm} \quad (30.2) \]

30.3 Interaction with Matter

Early experiments showed that x rays would penetrate matter. In fact, within one month after the discovery of x rays, two French physicists had produced a photograph showing the bones in a human hand. From experiments it has been found that the number of x-ray photons is diminished by passage through matter, particularly if they are passing through a material of high atomic number. It has also been found that some of the photons that emerge have the same energy as the incident energy, even though the number that emerge decreases as the thickness increases. For photons in x-ray energy range there are two physical processes that are of importance in reducing the number of x rays that pass through a material. These processes are the photoelectric effect and the Compton effect (scattering), which were discussed in Chapter 27.

First, the photoelectric effect as you recall is an interaction between the photon and an electron that is bound in an atom. The larger the number of electrons in an atom, the greater the probability that the photoelectric effect will occur. In the photoelectric effect the incident photon gives up its energy to a bound electron in an atom. The basic energy equation for this interaction is that the kinetic energy of the energy equation for this interaction is that the kinetic energy of the ejected electron is equal to the energy of the incident photon energy minus the energy required to remove the electron from its atom. In many cases, the work function is much smaller than x-ray photon energy, and the photoelectron has nearly the same energy as the incident photon. The photoelectron may also interact with matter. Secondly, the Compton effect, which we described in Chapter 27, is the interaction between a photon and a free electron. In this interaction the photon looses only a fraction of its energy. This loss of energy is imparted to the free electron. In general, the photon and the free electron are scattered at angles relative to the incident direction. The energy of the free electron depends upon the energy of the incident photon and the angles of scattering. As the atomic number of the material increases, the photoelectric effect becomes predominant over the Compton effect in reducing the x-ray intensity.
Both of the above effects are consistent with the fact that electromagnetic waves behave as particles, the photon concept. In each case the electron, first interacts with the incident x-ray photon, then interacts with matter as a charged particle.

### 30.4 Absorption Coefficient

The x-ray photons interact with matter through the photoelectric effect and Compton scattering. The photoelectric effect increases rapidly with $Z$, the atomic number of the target material. The photoelectric interaction probability is proportional to $Z^5$ and is the greatest for low-energy photons. The Compton effect is relatively independent of energy and the atomic number of the absorber. These two processes determine the absorption coefficient of the material for x rays. The intensity $x$ rays passing through a material of thickness $x$ can be expressed as an exponential function,
\[ I = I_o \exp(-\mu \Delta x) \] (30.3)

\( I \) is the x-ray intensity at a distance \( x \) in the material, \( \mu \) is absorption coefficient of the material, \( \Delta x \) is the thickness of the material, and \( I_o \) is the incident intensity of the x rays in joules per unit area per second.

For soft x rays (those with energy less than 50 keV) the photoelectric effect is the important factor in x-ray absorption, while for hard x rays (those with energy greater than 100 keV) the Compton effect contributes significantly to the absorption. The absorption coefficient as a function of energy for water (approximately the same as that of biological material) and for lead are shown in Figure 30.3.
EXAMPLE

Find the thickness of water required to reduce the intensity of 100 keV x rays by a factor of 1000.

From Figure 30.3, $\mu = 0.035$ cm. We want the value of $\Delta x$ that gives $I = 10^{-3} I_0$; thus we have

$$10^{-3} = \exp(-0.035\Delta x)$$ or $$0.035 \Delta x = \ln 1000$$

$\Delta x = (6.9078/0.035)$ cm $= 197.4$ cm $\sim 2$ m

It is worth noting that the relative absorption of bone to water is approximately 150. That is, bone is 150 times more opaque to x rays than is water. Lead is about 75 times more opaque than bone.

30.5 Detection of X Rays

The detection of x rays results from the effects of the energy absorbed in the detector. The fluoroscope uses the emission of visible light from a material when it is subjected to x rays. The photons emitted by the fluoroscope screen are in the visible region, and the observer sees a picture of the material through which the x rays pass before reaching the fluoroscope.

Photographic film is also used to record x rays. Small film badges are worn by persons in potential radiation areas as reliable detectors of radiation exposure.

An ionization chamber can be used to monitor the presence of x rays. A simple ionization chamber is represented in Figure 30.4. The chamber between a pair of parallel plates is filled with a gas at low pressure. The plates are connected in series with a source of DC potential of the order of 1000 V and with a current measuring device. A beam of x rays is directed along the long axis of the tube. The x rays are an ionizing agent, and as the atoms of the gas are ionized, the ions and the free electrons are subjected to an electric field. The positive ions are accelerated toward the cathode and the electrons and negative ions are accelerated toward the anode. This flow of ions produces an electric current between the plates and hence through the circuit. The current is proportional to the ions produced and thus to the energy of x rays absorbed.
Different types of ionization chambers are used in the detection of x rays. These differ in the geometry of the chamber and the magnitude of the applied voltage between the electrodes. One which is very useful in the detection of x rays is the Geiger-Mueller (G-M) counter. These counters are relatively economical, sensitive to x rays, rugged, and portable. They are generally made in a glass tube. The inside of the tube is coated to serve as the cathode and a coaxial wire serves as the anode (Figure 30.5).

The thickness of the entrance window determines the minimum energy of entering radiation for ionization. The tube is generally filled with an ionizable gas (argon and neon are often used) at a reduced pressure of about 0.1 atmosphere. Added to the major gas is a quenching gas (about 0.1 percent of which may be halogen). The ionizing radiation enters the counter, and ions are produced. The ions move in the radial field which is much stronger near the anode than positive ions do to the cathode. The avalanche of ions occurs along the electrode. The quenching gas and the circuitry are designed to impede a continuous discharge. The G-M counter is a pulse counting device, it has a high gas amplification ($10^6 - 10^9$), and the operating voltage is in the neighborhood of 1000 volts.

Another x-ray detecting system is a combination of a scintillation phosphor used in series with a photomultiplier tube. A photomultiplier tube has a photocathode which gives up electrons when struck by a photon. These electrons are focused on an electrode which will emit a multiple number $n$ of electrons when struck with an electron having an energy of about 100 eV. If the photomultiplier has ten electrodes, it has a gain of $n10$, where $n$ is usually 2 to 4. The final output from photomultiplier is conducted to the plate of the tube which is part of the electrical counting circuit. A diagram of photomultiplier is shown in Figure 30.6. Most of the phosphors have a very short decay time so this system is very useful for counting incident photons.
30.6 Radiation Units

Several units of radiation have been defined for use in working with the effects of radiation on living systems. The old unit of dosage of x rays is the roentgen (R). The roentgen is defined as that quantity of x rays that produces $1.61 \times 10^{15}$ ion pairs per kilogram in air. This is equivalent to 89 ergs ($= 89 \times 10^{-7}$ joule) per gram of air. The roentgen an exposure dose. The rad is the accepted absorbed dose that applies to any absorber and any type of radiation. The rad is defined as the radiation that releases $10^5$ joules per gram of absorbing material. Because different types of radiation produce different biological effects for the same amount of energy absorbed, other dosage units are defined as follows:

rem = rad equivalent man; the absorbed dosage that produces in man the effect equivalent to one rad of x rays

reb = rad equivalent biological; the absorbed dosage that produces in some biological material the same effect as one rad of x rays in that material.

The ratio of the rem to the rad is called the relative biological effectiveness (RBE) of the radiation. For example, fast neutrons have a RBE of 10, slow neutrons have a RBE of 2 to 5, alpha particles of 5 MeV have a RBE of 20, and electrons of 1 MeV have a RBE of 1. Some typical doses in rem are shown in Table 30.1.

<table>
<thead>
<tr>
<th>Source</th>
<th>Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>0.075 rem/year (varies widely) (up to 1 rem/year in India and Brazil)</td>
</tr>
<tr>
<td>Ra$^{224}$ in body</td>
<td>0.005 rem/yr</td>
</tr>
<tr>
<td>K$^{40}$ in body</td>
<td>0.000 rem/yr</td>
</tr>
<tr>
<td>Diagnostic x rays</td>
<td>0.2 rem/yr</td>
</tr>
<tr>
<td>Fall out</td>
<td>0.1 rem/yr (decreasing now)</td>
</tr>
<tr>
<td>Local dose of irradiation of tumors</td>
<td>(3000-7000) rem/treatment period</td>
</tr>
<tr>
<td>Lethal dose (whole body)</td>
<td>~ 400 rem at one time</td>
</tr>
</tbody>
</table>

30.7 Biological Effects of X Rays

The responses of living systems to ionizing radiation are complex and subtle. X rays are only one component of the radiations to which people are exposed.

The interaction of radiation with matter depends upon the absorption of energy, and the extent of biological damage depends upon the energy absorbed per gram in the organism.

Absorbed radiation produces physical changes in the cell. Some specific cellular changes that may occur are break-up of molecules, production of free radicals, inactivation of enzymes, change of deoxyribonucleic acid synthesis, and break-up of chromosomes. In addition gross physical changes may occur. Among these are increase of the viscosity of cellular fluids, increase of permeability of cellular membranes, swelling, and death. In many cases the effects are known, but the exact steps that occur between the absorption of energy and final results are not known. Also the absorption
of a constant amount of energy does not produce the same effect in all types of cells. As a sort of rule of thumb, cells that are growing rapidly are most susceptible to radiation. The most sensitive cells in the body are the bone marrow, lymphoid, and epithelial tissues. Cells of a fetus are very sensitive to radiation. The cells of bone, muscle, and blood vessels are less sensitive, and the nerve cells are the least sensitive, most resistant, to radiation.

It has not been established whether there is or is not a minimum absorption of radiation energy that is necessary to produce biological damage. There are different hypotheses relative to threshold. However, in general, once a level is reached in which the effect has been established, the total effect seems to be directly proportional to the absorbed energy.

The set of characteristic symptoms shown by individuals who have a large dosage in a short period of time is called acute radiation syndrome. You should realize that the response varies a great deal among individuals so the dosage size will suggest an overall average effect. For a whole body dosage of 25 rad, there are essentially no detectable effects. For dosages of 25 to 100 rad, the person shows little or no effects other than a detectable change in the blood count; lymphocyte count drops. Bone marrow, lymph nodes, and spleen are damaged. At 100-300 rad, one has blood changes, experiences vomiting, malaise, fatigue, and loss of appetite. With this dosage you would probably have to take antibiotics, but recovery would be expected. For dosage of 300-600 rad, the effects of lower dosage plus hemorrhaging, infection, diarrhea, loss of hair, and temporary sterility can be anticipated. A person receiving a dosage in this range will have to take antibiotics, have blood transfusions, and perhaps bone marrow transplant. About 50 percent of individuals exposed to this dosage range recover. Dosages above 600 rad produce the symptoms indicated above plus damage to the nervous system. Dosages of about 1000 rad and above produce almost certain complete incapacitation and death. In any case, death may be caused by a break down of either the circulatory or the respiratory system, or both.

In addition to the acute effects discussed in the previous paragraphs, there are delayed effects. These delayed effects may be in the exposed individual (somatic effects) or in his progeny (genetic effects). We will first consider the somatic effects.

The delayed somatic effects due to radiation are generally evident in the statistical study of a population.

The first known delayed effects occurred in the case of the bombings of Hiroshima and Nagasaki in the summer of 1945. Many of the survivors of these bombings developed leukemia, with the peak incidence of this disease developing in the period 1950-1952. There was also evidence of an increased incidence of other types of abnormal tissue growth among the survivors. Another example of diseases produced in humans as a result of exposure over a long period of time includes bone cancers, which occurred among workers who painted radium watch dials. These effects have been demonstrated in animal subjects in laboratory experiments.

The authors had a friend who considered his poor health in later years and eventually his death to be brought about by exposures which he received while working with the Manhattan Project for the development of an atomic bomb in the mid-
forties. This was a delay of about 20 years.

Some effects which have been produced by irradiation in animals are: shortened life time, lens opacities and cataracts in the eyes, and effects upon pregnant mothers, such as still-births, infant mortalities, mental retardation, abnormal physical development, and deformities.

In 1927 H. J. Meuller discovered that ionizing radiation produced gene mutation. Only the mutations which are produced in a gene cell can be transmitted to its progeny. These are known as genetic effects of radiation. The genetic changes in an offspring may be from minor changes to severe handicaps. The frequency of mutations induced by radiation depends upon both the dosage and the dose rate. It apparently becomes noticeable with dosage of the order of a 20-50 rads, and then increases linearly with total dosage. Also the frequency and type of mutation depends upon time of mating relative to the time of exposure. If a gene cell is already mature at time of mating, the irradiated cell carries a relatively high percentage of lethal mutations. If the mating occurs when the cell is immature the mutations will be predominantly recessive.

30.8 Radiation Protection Standards

The above discussion has probably raised the question in your mind, do we have any protective standards? The answer to the question is yes. For a comprehensive set of recommendations, see the report of the International Commission on Radiological Protection, ICRP Publication No. 9, Pergamon Press, London (1966). A brief statement of permissible dosage equivalents recommended by ICRP follows in Table 30.2.

<table>
<thead>
<tr>
<th>Exposed Group</th>
<th>Blood Forming Organs, Gonads, Lens of Eye</th>
<th>Other Organs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation workers</td>
<td>5 rem/yr after age 18; no more than 2.5 rem in any 3-month period</td>
<td>Skin, bone, thyroid, 30 rem/yr; hands, feet, forearms, 75 rem/yr; other organs, 15 rem/yr</td>
</tr>
<tr>
<td>Members of the public in vicinity of a controlled area</td>
<td>0.5 rem/yr</td>
<td>Skin, bone, thyroid, 30 rem/yr for adults, 15 rem/yr for children to age 16; hands, feet, forearms, 75 rem/yr; other organs, 15 rem/yr</td>
</tr>
</tbody>
</table>

Studies indicate that medical and dental x rays constitute the greatest single source for radiation for inhabitants of the United States. These are not under the control of the federal government. This means that risks are essentially the judgment of the licensed physician. However, some states have laws to control the acceptable standards of operation of irradiating units. In some states these regulations also apply to machines for shoe fitting, etc. However, these regulations do not cover radiation that you may get from other sources.


30.9 Medical Applications of X Rays

Diagnostic uses of x rays involve the differential absorption of different body parts for the x rays used. Almost all tissue will stop some x rays and cast a shadow on the fluoroscope. Diagnostic x-ray machines operate at energies less than 150 keV. For greater contrast it is sometimes necessary to insert a material with greater absorption than the organ. Barium salts and iodine compounds are either fed or injected into patients for this purpose.

The therapeutic value of x rays rests in their potential for killing living tissue. If a parallel beam of x rays is directed at a tumor with dosages of 2000 to 7000 rem, much if not all of the tumor can be killed. Therapeutic x rays may have energies of 5 MeV for deep-seated tumors. The energy deposited by the x-ray beam in the target tissue is designed to be lethal for that volume. The direction of the beam is usually altered during treatment so that tissue other than target tissue receives only small dosages of radiation.

EXAMPLE

A dentist uses an x-ray machine with 100 kV peak voltage. The machine operates at an exposure rate of 3 R/hr at a distance of 1 m from the machine.

a. Find the new exposure rate if the target current is increased by a factor of 10. The exposure rate is directly proportional to the production rate and the target current. Thus the new exposure rate will be 30 R/hr.

b. Find the thickness of lead required to bring the exposure rate back to 3 R/hr at the higher current. Using data from Figure 30.3, we find the absorption coefficient for lead (for 100 keV photons) to be 56.8/cm. Thus for \( I = I_0 e^{-56.8x} \), we can solve for the thickness of lead, \( x \).

\[
x = \frac{\ln 10}{56.8/cm} = 0.04 \text{ cm} = 0.4 \text{ mm}
\]

c. Find the distance from the machine that would also reduce the exposure to 3 R/hr assuming the inverse square law applies for the intensity in air. (What conditions are necessary for this to be a valid assumption?)
Assuming the intensity falls off as \( I/x^2 \), we have the following relation:

\[
3 \text{ (R/hr)}/1 \text{ m}^2 = 30 \text{ (R/hr)}/x^2
\]

Thus

\[
x^2 = 10.0 \text{ m}^2
\]

\[
x = 3.16 \text{ m}
\]
SUMMARY

Use these questions to evaluate how well you have achieved the goals of this chapter. The answers to these questions are given at the end of this summary with the number of the section where you can find related content material.

Definitions

Indicate whether the following statements are true or false. For the false statements, write a true statement using the italicized words.

1. The German railroad engineer who changes trains at *Bremsstrahlung* is called an *RBE*, railroad bremsstrahlung engineer.
2. The *characteristic x rays* from tungsten form a continuous background of *hard x rays* for the sharp *roentgen* lines of the source.
3. The number of *soft x rays* that stick to a ball of cotton is determined by the *absorption coefficient* of cotton.
4. The *absorption coefficient* of lead is computed for a thickness of 10 cm of lead as $0.1 \ln I/I_0$.
5. The radiation equivalent basic (*reb*) is equal to the radiation equivalent man (*rem*) divided by the relative basic effectiveness (*RBE*) of the radiation.

X-Ray Problems

7. An x-ray tube is operated at 50 kV.
   a. Find the highest frequency for emitted radiation.
   b. How much heat is produced by each accelerated electron that does not produce an x ray?

8. If a beam of x rays is incident upon material that has an absorption coefficient of 200 cm$^{-1}$, what thickness is necessary to reduce the number of emerging x-ray photons to one-half of the number of incident photons?

X-Ray Interactions

9. a. What are the basic sources of energy losses of x rays in matter?
   b. List at least three late somatic effects produced by x rays.

Answers

1. F (Sections 30.2, 30.6) 6. F (Sections 30.6)
2. F (Sections 30.2, 30.6) 7. a. $1.21 \times 10^{19}$ Hz;  b. $8 \times 10^{-15}$ J (Section 30.2)
3. F (Sections 30.2, 30.4) 8. $3.47 \times 10^{-3}$ cm (Section 30.4)
4. T (Section 30.4) 9. a. photoelectric effect, Compton effect (Section 30.3)
5. F (Sections 30.6)  b. leukemia, bone cancer, cataracts (Section 30.7)
ALGORITHMIC PROBLEMS

Listed below are the important equations from this chapter. The problems following the equations will help you learn to translate words into equations and to solve single concept problems.

Equations

\[ eV = hf_{\text{max}} = \frac{hc}{\lambda_{\text{min}}} \]  
(30.1)

\[ \lambda V = 1240 \text{ eV-nm} \]  
(30.2)

\[ I = I_o \exp(-\mu \Delta x) \]  
(30.3)

Problems

1. If \( f \) is the frequency, \( 5.12 \times 10^{18} \) Hz, for an x ray incident upon your body, what is its energy in electron volts and its wavelength in meters?

2. The potential across an x-ray tube used for diagnosis may be 25,000 V. What is maximum frequency of emitted x rays?

3. For a given wavelength (0.154 nm) of x rays, the absorption coefficient of aluminum is 132 per cm and that of lead is 2610 per cm. How thick should a sheet of aluminum be to give the same shielding effect as 1 mm of lead?

Answers

1. \( 2.12 \times 10^4 \) eV, \( 5.86 \times 10^{-11} \) m; 2. \( 6.03 \times 10^{18} \) Hz; 3. 1.98 cm

EXERCISES

These exercises are designed to help you apply the ideas of a section to physical situations. When appropriate, the numerical answer is given in brackets at the end of each exercise.

Section 30.2

1. The most energetic characteristic x rays from copper have a wavelength of 1.54 Å. Find the energy of these x rays. \([E = 8050 \text{ eV}]\)

2. An x-ray tube is operated at 40 kV. Find the wavelength of the most energetic x rays emitted from this tube. \([\lambda = 0.0309 \text{ nm}]\).

Section 30.4

3. The absorption coefficient for 0.154-nm x rays in nickel is 439 cm\(^{-1}\). Find the thickness
of nickel required to reduce the intensity of the incident x rays to 1/1000 of the incident value. \[ x = 1.57 \times 10^{-2} \text{ cm} \]

4. The linear absorption coefficients of 0.154-nm x rays in aluminum, nickel and lead are 132 cm\(^{-1}\), 427 cm\(^{-1}\), and 2600 cm\(^{-1}\) respectively. What thickness of each absorber is necessary to reduce the intensity of the beam to 10.0 percent of its original value? [174 \times 10^{-2} \text{ cm Al}, 5.4 \times 10^{-3} \text{ cm Ni}, 8.85 \times 10^{-4} \text{ cm Pb}]

5. If 1 cm of aluminum reduces a certain x-ray beam by a factor of 10 \((I = I_0 / 10)\), what thickness is needed, if the incident intensity is doubled, to maintain the same final intensity? [1.3 cm]

6. The intensity of an x-ray beam may be controlled by absorbers. Suppose that you have 10 identical sheets of absorbing material and that the intensity of the beam from the tube is \(I_0\). There is a loss of 10 percent in intensity when the beam passes through one sheet. Plot the intensity of the x-ray beams as a function of the number of absorbing sheets used.

Section 30.6

7. Find the amount of charge produced (either + or - charge) and 1 R of x-ray radiation in 1 g of air. \([2.6 \times 10^{-7} \text{ C/g}]\)

8. Find the energy needed to create an ion-pair in air. Use data from the definition of the roentgen. \([34 \text{ eV}]\)

PROBLEMS

The following problems may involve more than one physical concept. When appropriate, the numerical answer is given in brackets at the end of each problem.

9. If a spherical virus cell (assume same density as water) is destroyed by 500 keV x-ray photons (in single photon interactions), find the dose needed to kill 50 percent of a virus of 10-nm radius. \([.95 \times 10^9 \text{ rad}]\)

10. Find the energy per second deposited in a cube of water 10 cm on a side for 60-keV x rays in a 300- watt/m\(^2\) beam. The absorption coefficient for these x rays is 0.1 cm\(^{-1}\). \([1.9 \text{ joules/sec}]\)

11. Discuss each of the following factors as it relates to diagnostic x-ray use: voltage to x-ray tube, body type of patient, distance of patient from x-ray machine, part of body under study.

12. An x-ray examination is often used in diagnosing broken bones. What is the basic physical principal involved when using x rays in this capacity?

13. Many TV sets have been criticized because they emitted x rays. Why? If you have a set that does produce x rays, what safety factors would you recommend? Why?
14. What is the shortest wavelength that will be emitted by an x-ray target if the voltage across the tube is 10 kV? \([\lambda = 0.124 \text{ nm}]\)

15. Calculate the power supplied to an x-ray tube if it is operated at 50 kV and the current is 100 mA. \([5 \text{ kw}]\)

16. In an x-ray tube, the current to the target is 1.5 mA, and the voltage across the tube is 10,000 V. What is the wattage? How many electrons strike the target per second? \([15 \text{ watts}, 9.375 \times 10^{15} \text{ electrons/sec}]\)

17. What is the charge in coulombs passing through an x-ray tube for one-half second and a current of 80 mA? How many electrons strike the target per second? \([4 \times 10^{-2} \text{ C}, 5 \times 10^{17} \text{ electrons/sec}]\)

18. What is the velocity of an electron that is accelerated through a potential of 10,000 V as it reaches the target of an x-ray tube? \([\text{nonrelativistic, } v = 5.93 \times 10^{9} \text{ cm/sec}]\)