MEDICAL UNIVERSITY – PLEVEN
FACULTY OF MEDICINE

DIVISION OF PHYSICS AND BIOPHYSICS

LECTURE 14

LIGHT AND MODERN PHYSICS II

Clinical applications of electromagnetic waves. Medical imaging with CT and NMR scans. The laser and its applications

CLINICAL APPLICATIONS OF EM WAVES

A number of clinical treatment techniques and diagnostic processes make use of EM waves.

All types of EM waves are physically similar, differing only in frequency and wavelength.

Yet different EM waves have very different physiological effects.

E.g. Human body is transparent to radio waves, becomes opaque as the frequency rises to the visible light region, and becomes more transparent again to X-rays.

The physiological effects of EM waves are different because the quantum energies ($E = hf$) are different, and they produce different types of physical interactions.

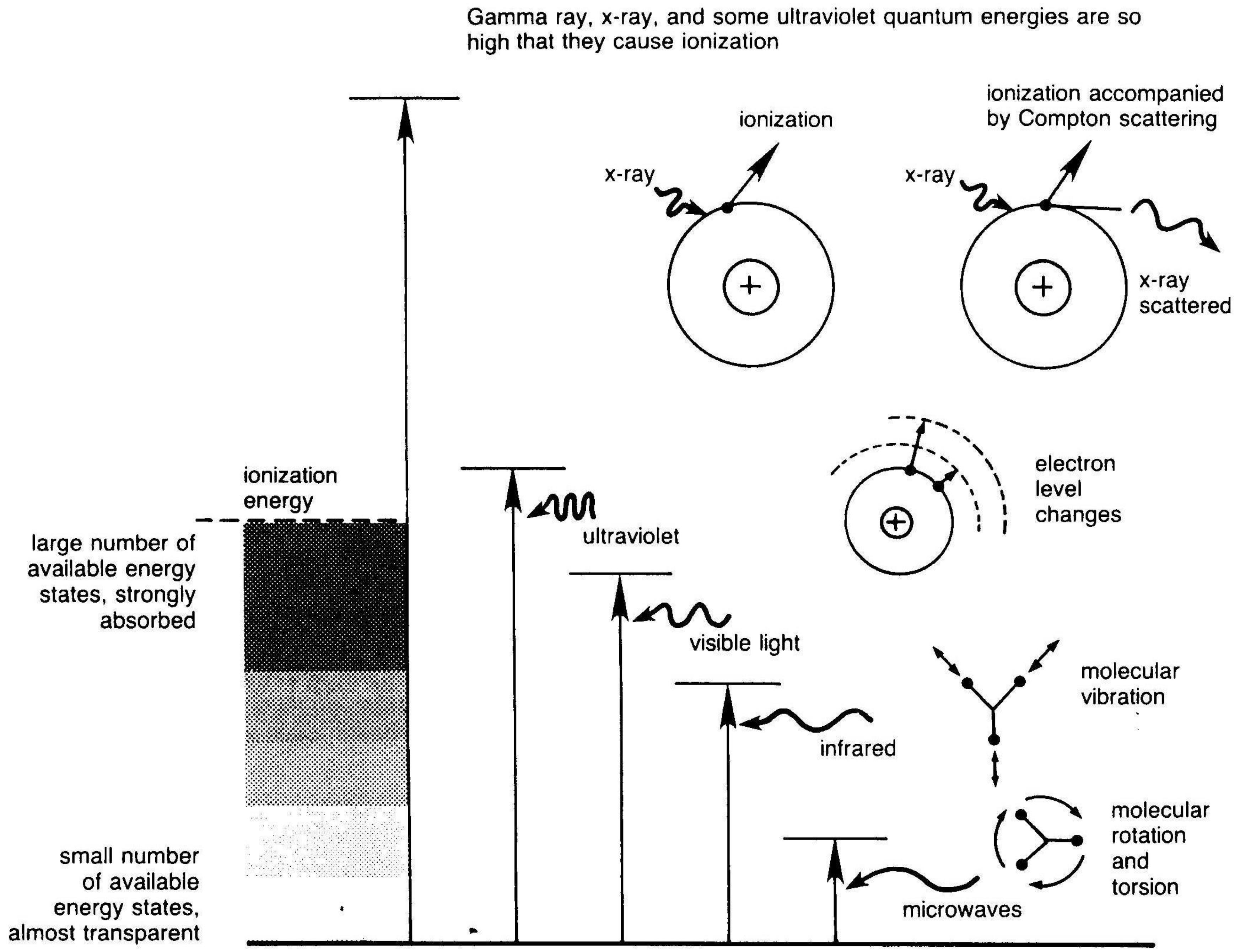
The nature of the physiological effect depends upon how strongly the radiation is absorbed.

If a substance has many pairs of energy states corresponding to a given radiation frequency, then that radiation will be strongly absorbed. If there are no pairs of energy states ($\Delta E \neq hf$), then the material will be transparent to that frequency.

There are very few mechanisms by which tissue can absorb the lower radio frequencies, so they pass through almost unattenuated.

In the microwave region E of the photons are large enough to cause molecular rotation and torsion, which is experienced as heat.

Infrared radiation causes molecular vibration: periodic stretching or torsion of internal molecular bonds. It is absorbed more strongly, but the associated changes in internal energy (heat) are close to the surface rather than the volume changes.


Gamma ray, x-ray, and some ultraviolet quantum energies are so high that they cause ionization
ionization
ionization accompanied by Compton scattering
x-ray
x-ray
x-ray scattered
electron level changes
ionization energy
large number of available energy states, strongly absorbed
ultraviolet
visible light
molecular vibration
infrared
molecular rotation and torsion
microwaves
small number of available energy states, almost transparent

In the visible and ultraviolet ranges the quantum energies are large enough to excite electrons to higher orbits. Since there are vast numbers of available electron energy levels, these EMW are absorbed strongly and generally do not penetrate past the skin.

The available energy levels for ultraviolet photons are so dense that all incident ultraviolet radiation is usually absorbed in a very thin outside layer of the skin.

When the EMW frequency is increased into the upper ultraviolet or into the X-ray or'Y ray ranges, E of the photon is so large that it can only be absorbed by disrupting the atom or molecule (ionization).

RADIO FREQUENCY AND MICROWAVE RADIATION

Medical applications involve frequencies from

500 kHz to 2500 MHz.

The lower part of this range is classified as the radio frequency region and the upper part - the microwave region.

The effect of such radiation - molecular agitation (heat).

The therapeutic effectiveness of radio- and microwaves - they penetrate the body and raise **T**.

The use of such radiation for heat therapy is referred to as diathermy **(for relief of muscular pain, inflammation of the skeleton and other conditions in which warming of deep tissues is beneficial).**

Although such radiation does not produce chemical changes in the body as in the case of X-rays, it may produce internal burns with excessive exposure and may produce surface burns if the coils or transmitting elements are in contact with the skin.

INFRARED RADIATION

The term "infrared" refers to a broad range of frequencies, beginning at the top end of frequencies used for communications and extending up to the low frequency end (red) of the visible light.

λ=1 mm (10^{-3} m) - 7500 A (7.5×10^{-7} m).

The low frequency end of the infrared range is called the "far infrared" range and the upper end is called the "near infrared" range, referring to its separation from the visible light region.

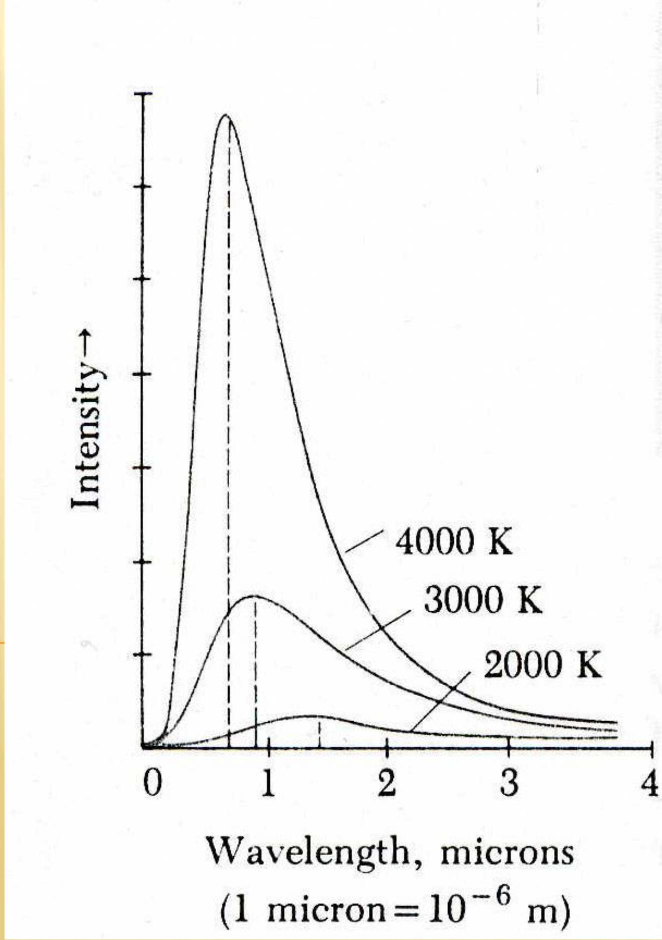
Most medical applications of IR radiation make use of the near infrared range, extending below the visible range from λ=7500 A -30,000 A.

Any hot object gives off infrared radiation. From a classical viewpoint it originates from accelerated charged particles near the surface of the object which emit radiation much like small antennas. The thermally agitated charges produce continuous spectrum of radiation.

By the end of the 19th century, it had become apparent that the classical theory of thermal radiation was inadequate.

Basic problem - in understanding the observed distribution of λ in the radiation emitted by a black body.

Def. A black body is an ideal system that absorbs all radiation incident on it.

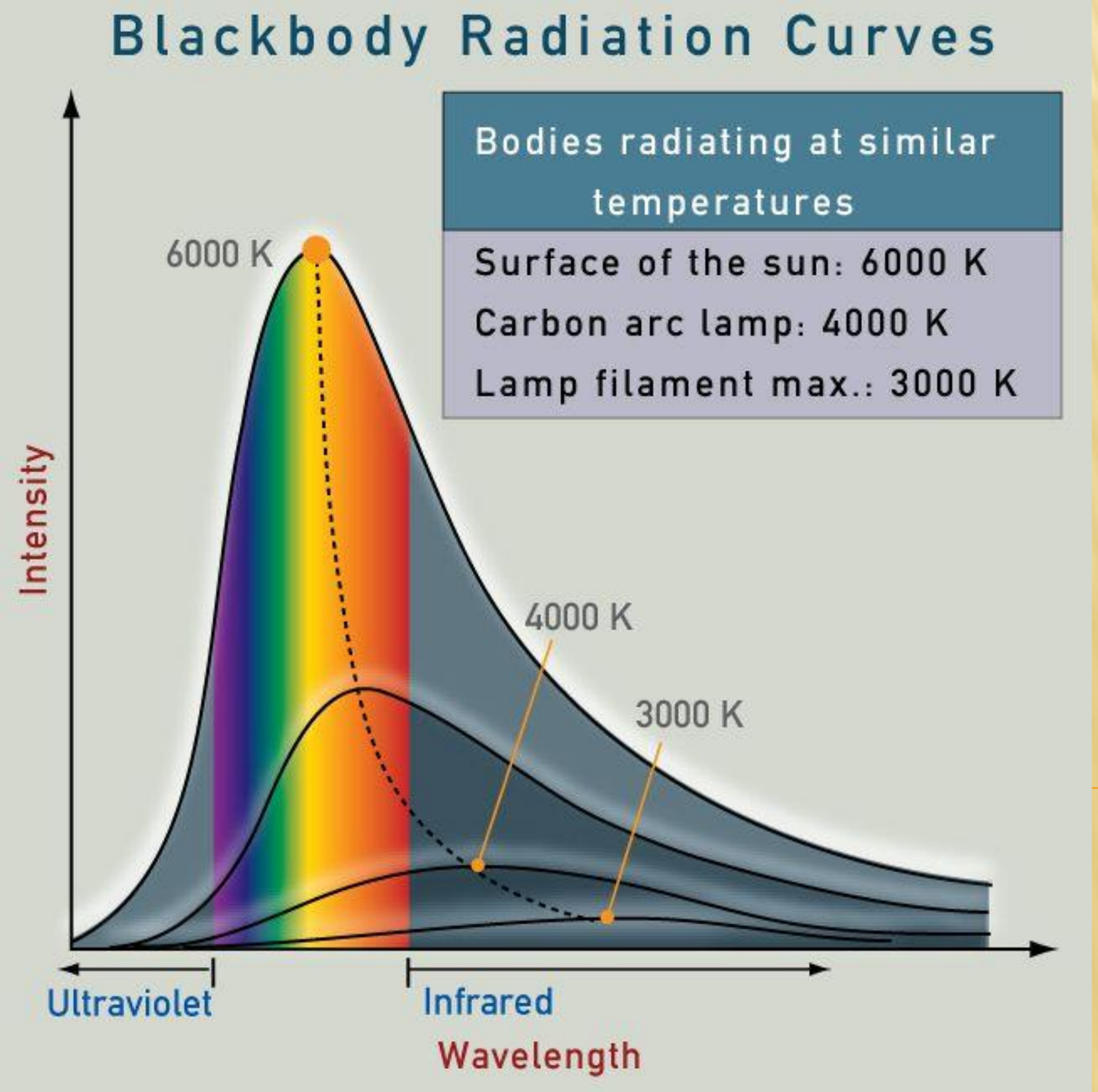


A good approximation to a black body is the inside of a hollow object. The nature of the radiation emitted through a small hole leading to the cavity depends only on the temperature of the cavity walls.

The radiated energy varies with λ and T. As the temperature of the black body increases, the total amount of energy it emits increases.

With increasing T, the peak of the distribution shifts to shorter λ. This shift was found to obey the **Wien's displacement law:**

$$\lambda_{max} \times T = 0.29 \times 10^{-2}\ \mathrm{mK}$$



Thus, a hot object emits a broad band of frequencies of radiation, with the relative intensity of the radiation as a function of frequency following a well-defined distribution curve.

If the temperature of the object is raised, the radiated energy increases and the frequency at which the intensity peaks also increases.

The higher temperature implies that the object has more internal energy to be released in the form of EM waves, hence brightness increases.

Infrared lamps are sometimes used for heat therapy, but the characteristics of such warming is quite different from the diathermy.

Infrared radiation tends to cause molecules to vibrate, and the radiated energy is absorbed very quickly.

Infrared waves do not penetrate very far into the body and are not suitable when the therapeutic effect desired is the warming of deep tissues.

Infrared waves do penetrate more deeply than visible light, and this fact has been used to advantage in infrared photography for diagnostic purposes.

1. Since infrared light penetrates the skin, it can be used to photograph veins and other structures beneath the skin which are invisible to the eye.

2. Infrared photography can be used to study the pattern of healing under certain scabs and for diagnostic studies of the eye.

The human body is an efficient radiator, and the peak of radiation curve is in the infrared region. An image of the human body can be formed using sensitive infrared detectors. This is referred to as infrared thermography.

A brighter image in a given region implies that the region is at a higher T, so the thermograph is essentially a display of T variations of the skin.

The contrast of the image might be enhanced by filtering out lower frequencies to make use of the fact that the peak frequency also shifts upward with increasing temperature.

One use of the thermograph is for the early detection of breast cancer. The temperature of a tumor will often be 1°C to 2°C higher than that of normal tissue, and skin temperature elevations of as much as 5°C are recorded as a result of breast cancer.

Thermographs are also used for the examination of burns and frostbite, and for the analysis of the vitality of various types of skin grafts.

The thermograph receiver is a sensitive infrared detector which scans over successive small strips of area and converts the infrared intensity into an electrical signal which is amplified and displayed on an oscilloscope screen.

The brightness of the display depends upon the number and speed of the electrons which strike the phosphor screen.

The display may be photographed for a permanent record.

ULTRAVIOLET RADIATION

UV radiation ranges upward in frequency and quantum energy from the high frequency end of the visible light range (the violet end) to the low frequency end of the x-ray range (λ=4000 - 400 A).

“Near-ultraviolet" range λ= 2500 - 4000 A (250-400 nm).

UV radiation is absorbed strongly by most forms of matter, even air. The separations between allowed e^- energy levels in many atoms and molecules correspond to photon energies in the UV range.

The high energy UV photons may:

- excite e- to higher levels,
- eject e- from atoms or molecules to form ions,
- dissociate molecules into their constituent atoms, or produce other chemical changes.

Even though the sun is a strong source of UV radiation, very little radiation below λ=3000 A reaches the earth.

The atmospheric gases, chiefly oxygen and ozone, absorb the radiation before it reaches the earth. Therefore, depletion of the ozone layer by atmospheric contaminants could have very serious consequences.

Sunburn is largely attributable to the UV rays which do penetrate the atmosphere.

Since the higher frequency UV rays can cause ionization, UV has been implicated as a cause of skin cancer. UV radiation normally does not penetrate into tissue deeper than about 1mm. It can be used therapeutically for the treatment of skin conditions such as psoriasis and acne and for certain cosmetic effects.

The radiation is also effective for killing fungi and bacteria on the skin and for instrument sterilization.

The eye is most susceptible to damage by UV light. Welders must wear protective eye shields because the UV light from a welding arc can produce acute inflammatory conditions of the eye.

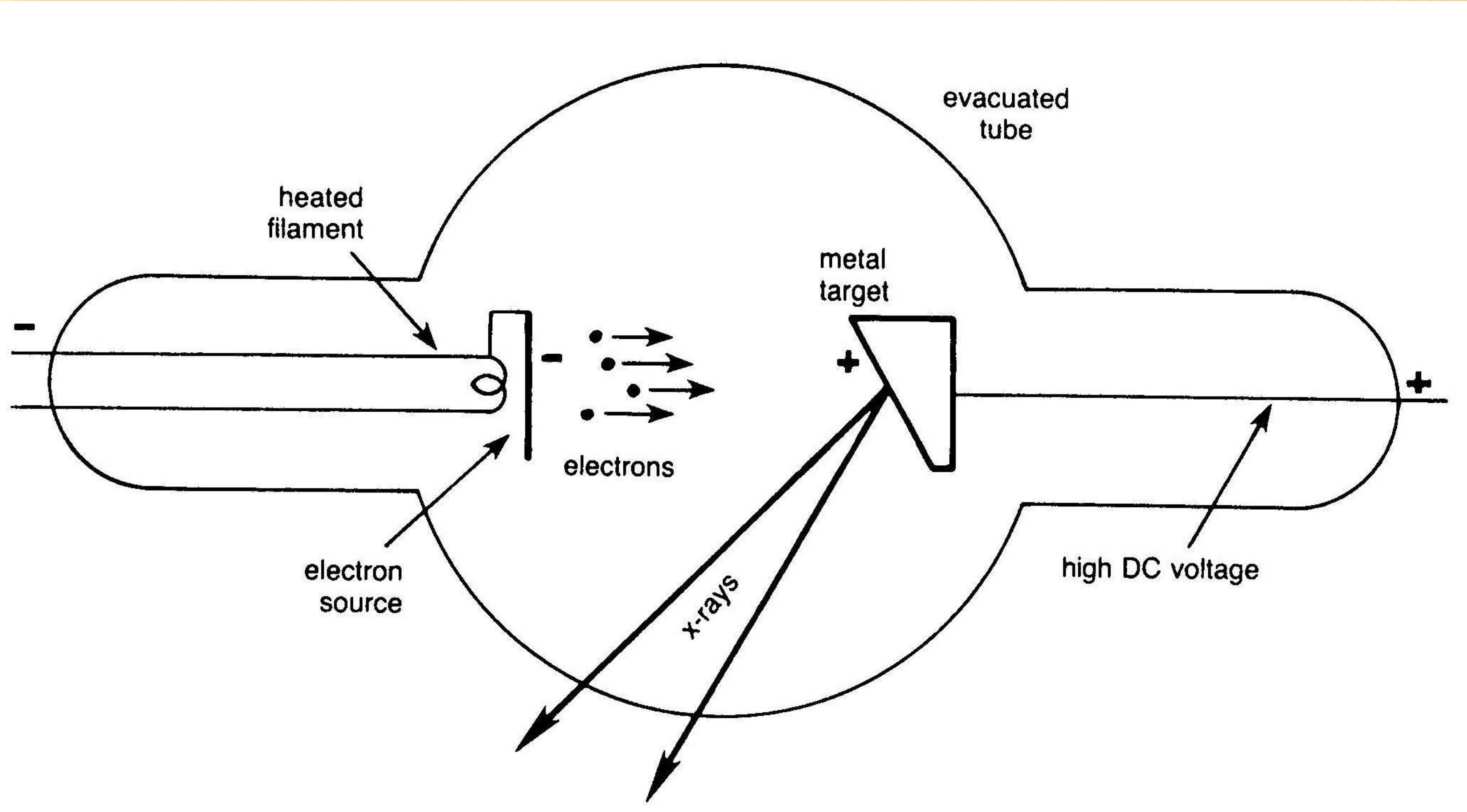
X-RAY RADIATION (λ = 100 - 0.1 A)

X-rays are essentially the same as gamma rays, except that the term "gamma ray" refers to radiation which originates in the nucleus and which generally has higher energies.

Production: They can be produced by accelerating electrons through high voltages (20 to 200 kV) and allowing them to strike a metal target.

When the high speed electron approaches a metal atom, it is strongly repelled and decelerated by the electron cloud of the atom, thereby losing kinetic energy.

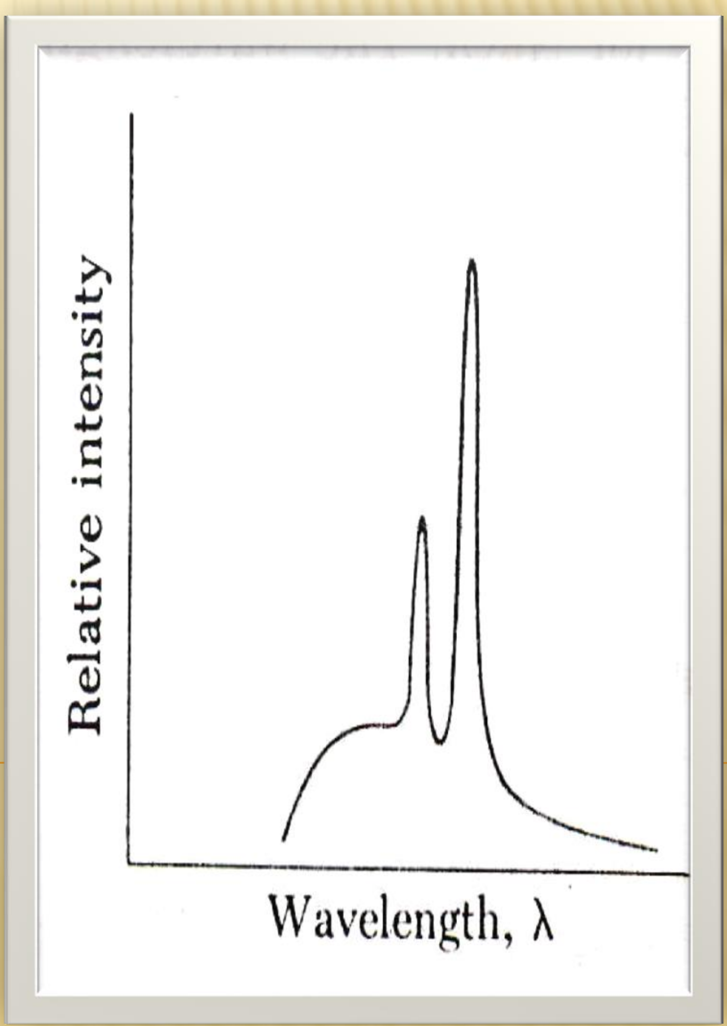
Most of this energy goes into raising T of the metal target, but about 1% of it is given off as X-rays.



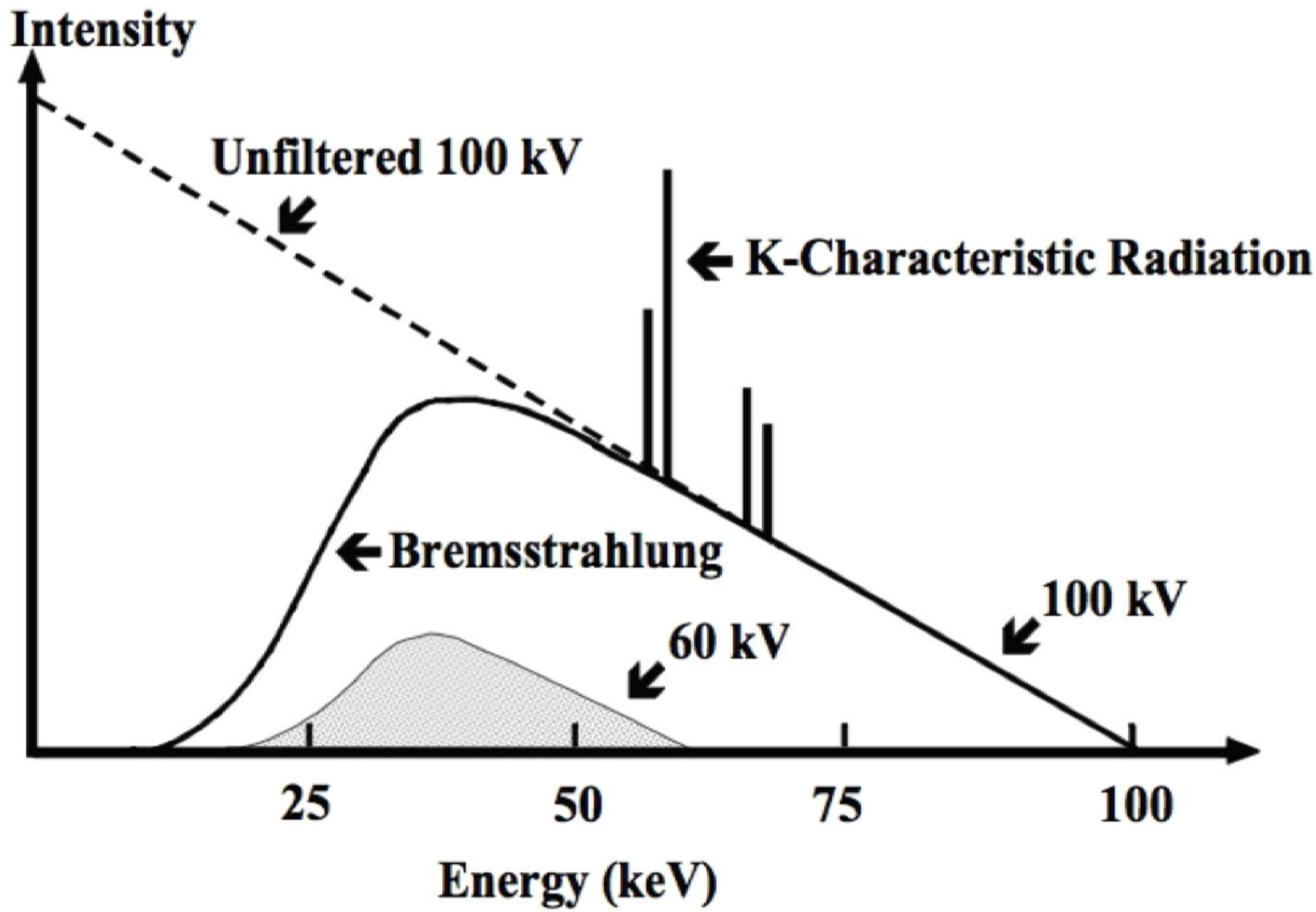
Because different e^- may be decelerated at different rates, X-rays can be produced with a wide spread of λ.

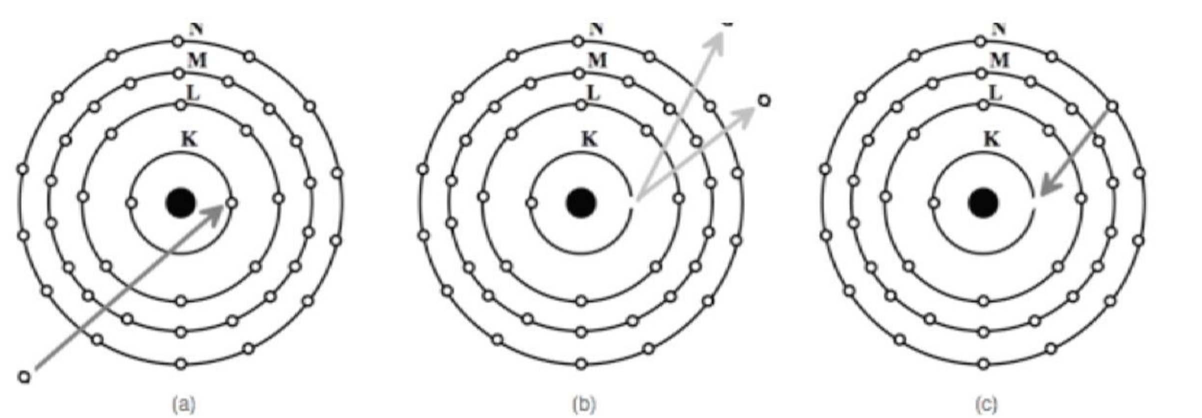
This process is essentially the reverse of the photoelectric effect. There are two distinct patterns:

1. a continuous broad spectrum that depends on the voltage applied to the tube.



2. Superimposed on this pattern is a series of sharp, intense lines that depend on the nature of the target material. The accelerating voltage must exceed a certain threshold voltage, in order to observe these sharp lines, which represent radiation emitted by the target atoms as their electrons undergo rearrangements.


Intensity
Unfiltered 100 kV
K-Characteristic Radiation
Bremsstrahlung
100 kV
60 kV
25
50
75
100
Energy (keV)


N
M
L
K
(a)
(b)
(c)

The continuous radiation is sometimes called *Bremsstrahlung*, a German word meaning braking radiation.

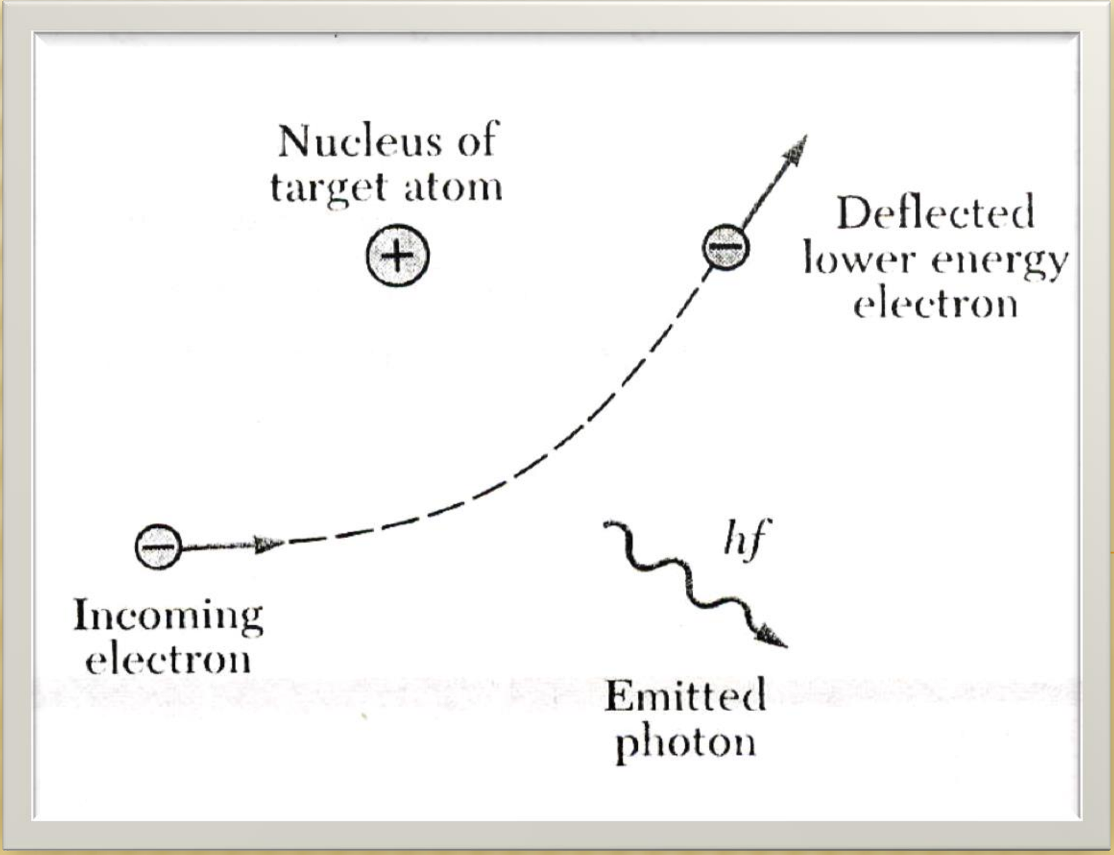
As an electron passes close to a positively charged nucleus contained in a target material, it is deflected from its path because of its electrical attraction to the nucleus, and hence experiences an acceleration.

Classical physics shows that any charged particle will radiate energy in the form of EM radiation when it is accelerated. According to quantum theory, this radiation must appear in the form of photons.

Since the radiated photon carries energy, the electron must lose kinetic energy because of its encounter with the target nucleus.

Let us consider an extreme example in which the electron loses all of its energy in a single collision. The initial energy of the electron (eV) is transformed completely into the energy of the photon (hf_{max})

$$eV = hf_{max} = \frac{hc}{\lambda_{min}}$$



An electron passing near a charged target atom experiences an acceleration and a photon is emitted in the process.

The shortest-wavelength radiation produced is

$$\lambda_{min} = \frac{hc}{eV}$$

The radiation does not have this particular λ because many of the electrons are not stopped in a single collision. This results in the production of the continuous spectrum of λ.

X RAY ATTENUATION MECHANISMS

The quantum energies of X-ray photons are so great that they are not strongly absorbed by ordinary tissue.

They can be absorbed only by disrupting atoms or molecules, and probability for such violent events is lower than for other absorption processes.

If the entire quantum energy of an X-ray photon is absorbed, it will generally eject an electron in the photoelectric process. The electron will be ejected with $\boxed{E_k=hf-W}$, where W is the work required to tear the electron out of its molecular environment. Usually this ejected electron will have enough energy to ionize many other atoms.

For example, a typical X-ray photon used in diagnostics might have an energy of 50 keV. By comparison, it would take only 13.6 eV to strip the electron from a hydrogen atom, leaving the ejected electron with enough surplus energy to cause the ionization of many other atoms.

A more common interaction in the energy range used for diagnostics is Compton scattering. The incident X-ray photon gives only a fraction of its energy to the ejected e-, with the remainder "scattering" off as a lower energy photon.

The ejected electron, however, will have enough energy to ionize many atoms in the vicinity of the original event.

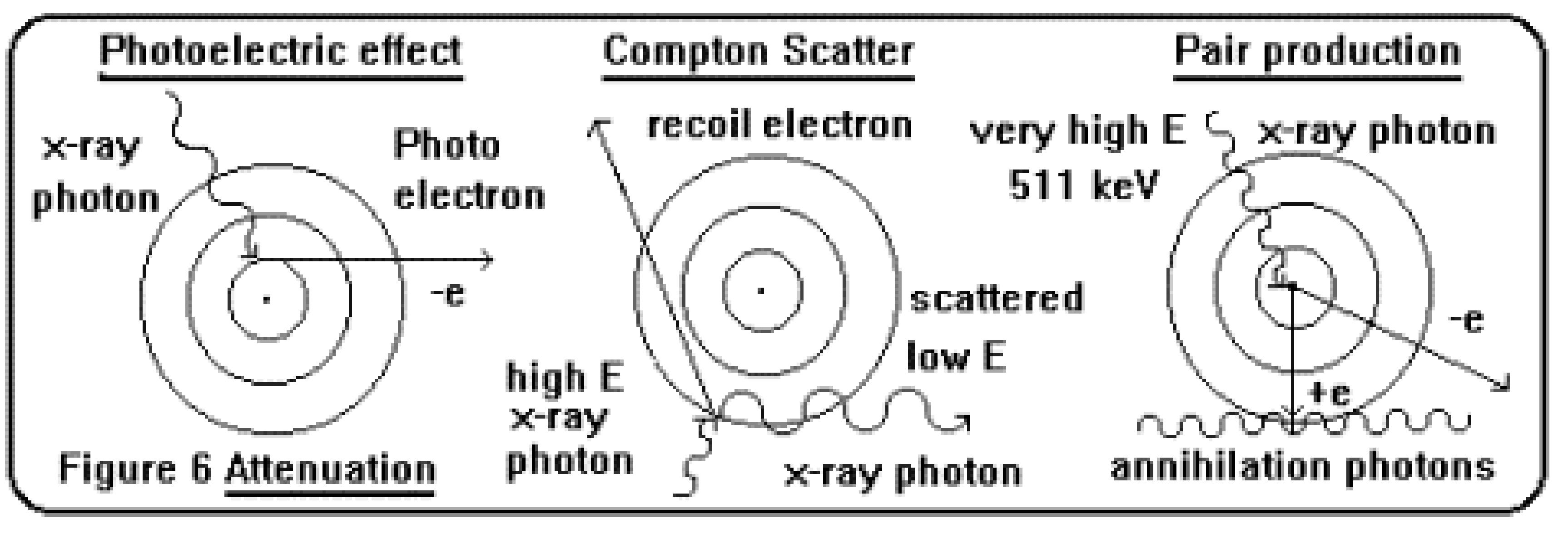


Figure 6 Attenuation

Neither interaction has a high probability, so most of an X-ray beam would be expected to pass through normal tissue without interacting.

The ionizing capability sets X-rays and γ rays apart from the lower frequency EM waves. The **disruptive ionization events**, though relatively small in number, can cause **biological damage**.

While the benefits to be derived from diagnostic X-rays generally far outweigh the risks, they should nevertheless be used conservatively.

1. The fact that the soft tissues of the body are more transparent to X-rays than the bony structures can be used to form a shadow pattern.

2. The same technique can be used for the X-ray examination of organs, but the difference in X-ray transmission by different soft tissues is quite small.

   One way to increase the contrast is to introduce air or another gas into a cavity normally filled by fluid. The X-ray absorption of the air is lower than that of the tissue, providing the needed contrast.

In other areas it is easier to increase the contrast artificially by inserting materials which are nearly opaque to X-rays (**barium sulfate** is for examining the upper and lower gastrointestinal tract).

The energy level separations are small in the lighter atoms such as carbon, oxygen, and hydrogen and they are nearly transparent to X-rays.

Heavier elements such as barium and lead have energy levels in their inner shells which have separations comparable to the X-ray photon energies and therefore readily absorb X-ray (lead is the common shielding material because of its reasonable cost and availability).

DIGITAL SUBTRACTION ANGIOGRAPHY

Angiography is the process of injecting a dye containing heavy-element X-ray absorbers into the blood vessels to enhance their X-ray contrast compared to their tissue backgrounds. With a computer, an X-ray image can be “digitized.“

If this digitizing process is done for an X-ray taken before the dye is injected into the blood vessels of interest, and then repeated with the dye, the first image can be digitally subtracted from the second by computer. This leaves only that part of the image which has changed.

MEDICAL IMAGING WITH CT SCANS

Even with the methods for enhancing contrast, the conventional X-ray photograph is essentially a shadow picture, making accurate diagnosis difficult. Major advances have been made with computer-assisted scanning methods which produce a cross-sectional view of part of the body - the so-called computed tomography or CT scans.

If a thin pencil-beam of X-rays is passed through a section of tissue a number of times from different directions so that all the beam exposures have **a common crossing point**, the results can give a detailed evaluation of the X-ray absorption at that crossing point.

With multiple x-ray beam and multiple detectors, modern scanners can collect such information about thousands of points within a few seconds of exposure time, storing the information in a computer memory for the purpose of constructing a two-dimensional view of the x-ray absorption of a section of the body.

A tomograph is an image of a slice, from tomos, the Greek word for slice.

The particular advantage of an X-ray tomograph is that it presents a cross-sectional image of the X-ray absorption in a slice of the body so that accurate relative locations of the absorbers are given.

The rapid multiple exposures of a CT scan give multiple images, which can then be back-projected as part of the image-forming process. The back projection reveals the relative positions of the absorbers in the crossing area of the multiple beams.

Besides storing the data, the computer is used to process it to eliminate distortions of the image which arise from the nature of the technique, and to produce a finished display on a TV screen.

CT scans can detect changes in X-ray absorption on the order of 100 times smaller than the minimum detectable changes on conventional X-ray photographs. Spatial detail as small as 1 mm can be resolved.

THE LASER AND ITS APPLICATIONS

The word LASER is an acronym representing Light Amplification by Stimulated Emission of Radiation.

The property of laser light which has made it valuable for medical applications is

- ✓ the collimation of the light in a very narrow beam
- ✓ light can be further focused to an almost microscopic point, yielding enormous energy densities in the area of focus.

The emission of light by a material is associated with the transition of an atomic electron from a high energy state to a lower one. An e^- will tend to move to the lowest available energy level, and this leads to the spontaneous emission of a photon whose energy, is

$$E = hf = E_2 - E_1.$$

If a photon of energy E interacts with the atom while the electron is in the lower level E_1 it may be absorbed, raising the electron to energy E_2.

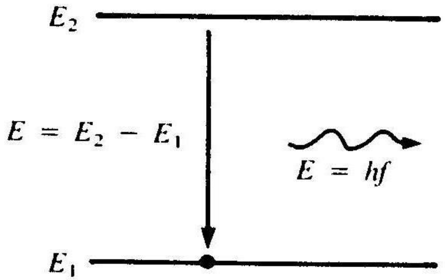
If the photon interacts with the atom when the e^- is in the higher state E_2, it may cause it to make the downward transition sooner than it would have by the spontaneous process - stimulated emission.

Therefore, if a large number of photons of this energy are incident upon the material, both absorption and stimulated emission occur.

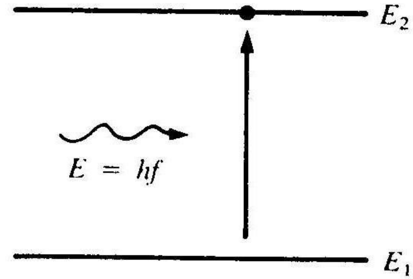
For normal materials, more e^- will be in the lower state, so absorption would occur more frequently.

If a population inversion can be produced by some means so that the upper states have more electrons than the lower states, then light amplification can be achieved.

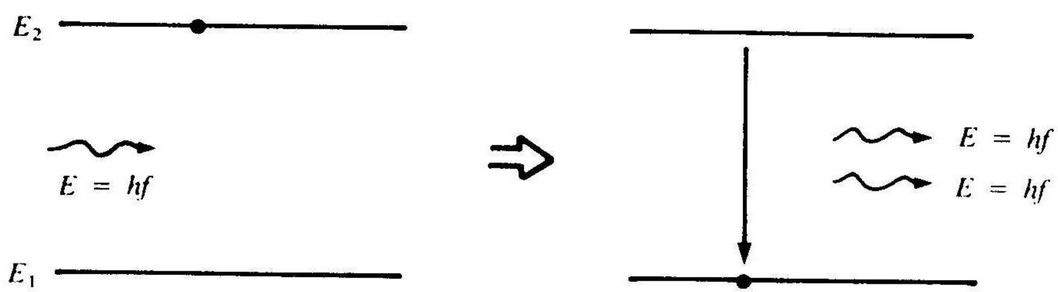
A chain reaction can occur, with one photon triggering the emission of another photon and proceeding to produce two more, until a large number of photons is produced.



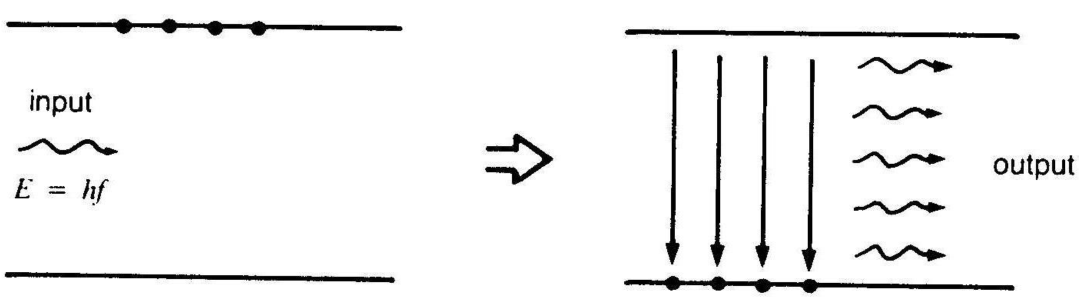
(*a*) emission of a photon



(*b*) Absorption and upward transition



(*c*) Stimulated emission of radiation



(*d*) light amplification by stimulated emission of radiation (laser)

The discovery of the laser was basically the discovery of how population inversions could be practically achieved.

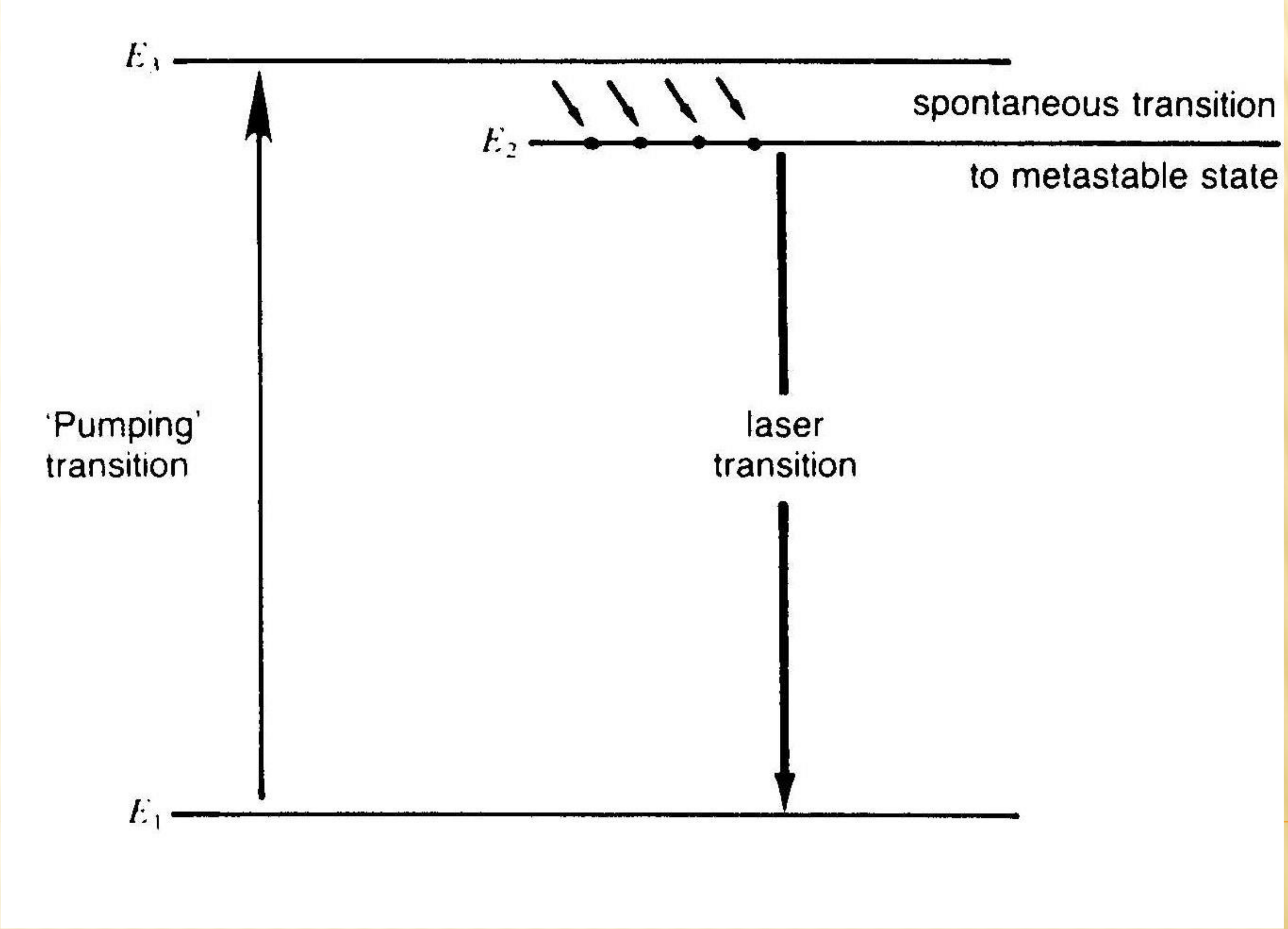
It cannot be done with just two atomic energy levels, since the photons that are sent in to "pump" electrons up to the higher level are just as likely to cause a transition out of the upper level (stimulated emission).

The situation is further complicated by the fact that most excited states of atoms have very short lifetimes (10^{-8} s). However, there are some atomic and molecular excited states which have much longer lifetimes, existing from **10^{-6} s** up to several **min** before an e- makes a downward transition – the metastable states.

These states can be populated by using three energy levels. The electrons are first "pumped" into a higher energy level, E_3, by supplying energy in the form of light, electric discharge, or high energy molecular collisions.

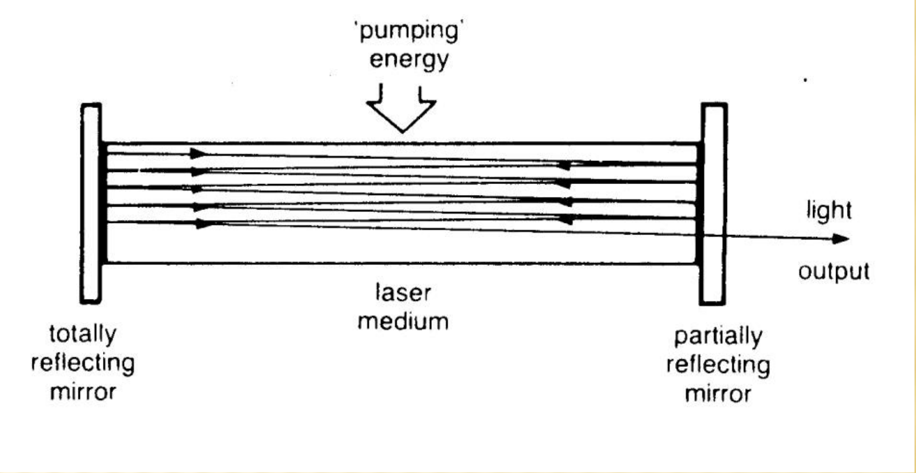
The elevated electrons then drop quickly into the metastable state E_2 by spontaneous emission or loss of energy through collisions.

A large population inversion can be obtained because the electrons will remain in state E_2 for a considerable length of time. When a photon of appropriate energy interacts with one of these "trapped" electrons, it stimulates the e- to emit a photon.


E_3
spontaneous transition
to metastable state
E_2
'Pumping' transition
laser transition
E_1

To improve the efficiency of the laser it is important to have the light pass through the laser medium several times, since the light is amplified each time it passes through. This is made possible by placing parallel mirrors at the ends of the laser medium.

One mirror is nearly totally reflective and the other is usually made partially reflective to let some light out upon each reflection.



Very precisely aligned mirrors are required to get efficient laser action; this is the most critical mechanical factor involved in constructing the laser.

The facts that the laser beam is made up of very nearly parallel rays and that it consists of only one λ make it possible to focus the beam to an extremely tiny spot. The widest medical use of the laser has been in **ophthalmology**.

A laser, emitting light **in short bursts**, has been proven very effective in **photocoagulation of the retina.**

Hemorrhages in the retina may be treated by focusing intense light through the lens of the eye onto the affected part of the retina.

A further advantage of the laser treatment is the fact that the beam can be focused on an area having a diameter of 50 μm. This is important if the treatment area includes the fovea.

The fovea is essential for color vision. This spot is only about 10^3 μm in diameter. Therefore, the small focus area of the laser is essential if photocoagulation is to be attempted in this region.

The laser is also the preferred method for treating retinal tears and detachments and some other retinal conditions.

The enormous energy density and precise focusing of the laser beam may lead to wider applications in delicate surgery. In addition to precision, the beam has a cauterizing effect and offers the possibility of bloodless surgery in specific applications.

The effects of high intensity light on pigment molecules have led to experimental use of the laser for removal of birthmarks and tattoos.

HOLOGRAPHY: THREE-DIMENSIONAL IMAGES

One of the applications of laser is the production of **three-dimensional images** by a process known as holography. Holography is a photographic process, but instead of forming a focused image on the film with the use of a lens, the film is exposed to the reflected light from the object.

Part of the light from the laser is reflected from a mirror and directed toward the film where it mixes with the light reflected from the object.

The film records the interference between these two beams of light and produces a photographic pattern of irregular fringes with no resemblance to the object when viewed in ordinary light.

However, these interference fringes contain more information about the object than an ordinary photograph. It is as if the light wavefront from the object were "frozen" on its way to your eye.

When the wavefront is reconstructed by passing laser light through the film, a three-dimensional image is perceived in space behind the film.

If one part of the image is hidden from view, it can be seen by moving your head to one side in exactly the same manner that you would move to see all parts of the real object.

In fact, a full 360^0 hologram can be made to allow you to rotate the hologram and see all sides of the object.

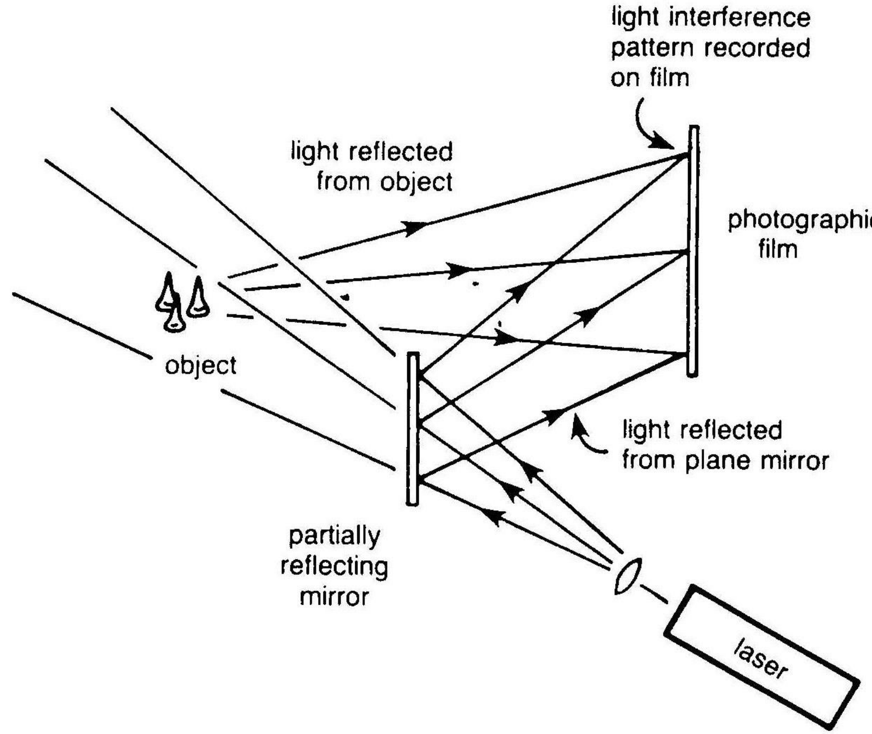
A hologram cannot be made with ordinary light because such light is "incoherent“.

The coherence of laser light is one of its most important properties - the waves can interfere with each other constructively or destructively.

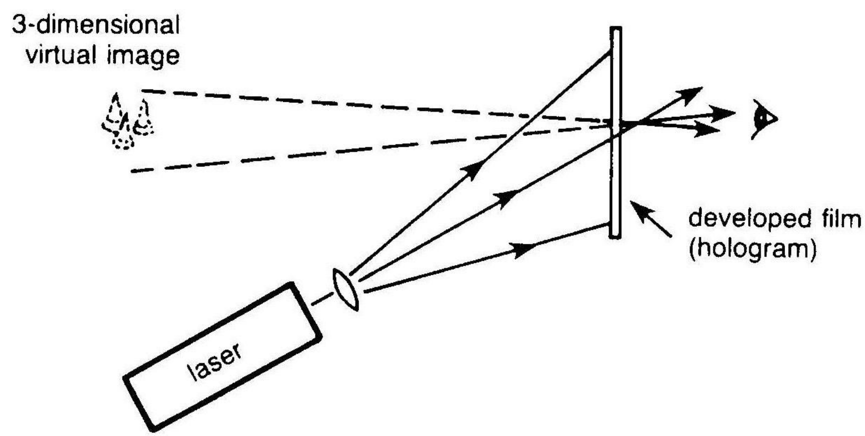
It is this interference which allows the information to be recorded on the film.

First practical applications of holography were - in the area of microscopy. Besides the obvious advantages of a three-dimensional recording of microscopic events, the hologram provides improved resolution.

The theoretical limits of resolution for microscopy are set by the wavelength of the light and the size of the lens aperture.



(a) The photographic process



REVIEW QUESTIONS

1. What does "quantization" mean with regard to physical properties? What physical properties of atoms are quantized?

2. What is the difference between light and x-rays? What is the difference between x-rays and radio waves?

3. What features of the photoelectric effect experiment could not be explained by a classical wave theory of light?

4. From the point of view of the quantum theory of light, what explanation could you offer for the fact that x-rays produce damaging radiation effects in the body, while radio waves do not?

5. Describe the effect of a barium sulfate solution taken before a stomach x-ray.

6. What precautions should be taken when administering an ultraviolet treatment?

7. What type of radiation is primarily responsible for sunburn?

8. How can the light emitted by a substance be used to identify the chemical elements present in the substance?

10. What are the properties of the laser which make it medically useful?

11. What would be the advantages of an acoustic hologram over x-rays as a tool for the study of internal organs and bones?