MEDICAL UNIVERSITY – PLEVEN
FACULTY OF MEDICINE

DIVISION OF PHYSICS AND BIOPHYSICS

LECTURE 13

LIGHT AND MODERN PHYSICS *part 1*

The electromagnetic spectrum. The quantum theory of light. Matter waves: The electron microscope. Quantum theory of the atom. The interaction of electromagnetic waves with matter

One of the characteristics of the classical concepts of mass, velocity, acceleration, etc., is that they have a continuous range of values.

When phenomena on the atomic scale are considered, many physical variables are "quantized" - they can take only certain discrete values, and all other values are forbidden.

The modified framework of physics necessary to explain such phenomena is often referred to as QUANTUM MECHANICS or QUANTUM PHYSICS.

THE ELECTROMAGNETIC SPECTRUM

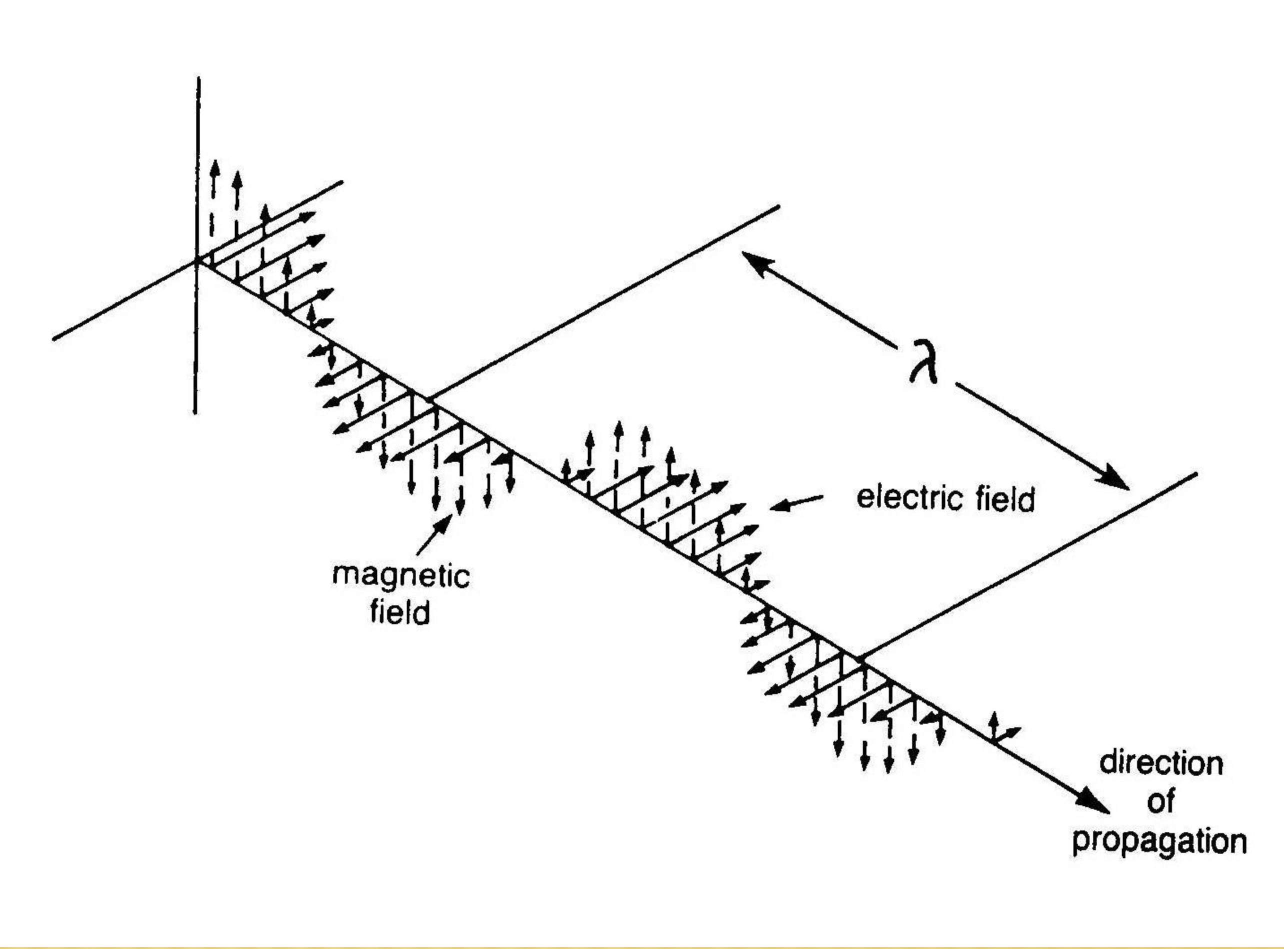
Visible light, X-rays, microwaves, and the radio waves are examples from the broad class of electromagnetic waves.

They have characteristic frequencies, wavelengths and amplitudes. Unlike sound, they do not require a material medium through which to travel.

EMW propagate freely through empty space at enormous speed $c = 3 \times 10^8$ m/s.

They are transverse waves that can be visualized as electric and magnetic fields distributed in space.

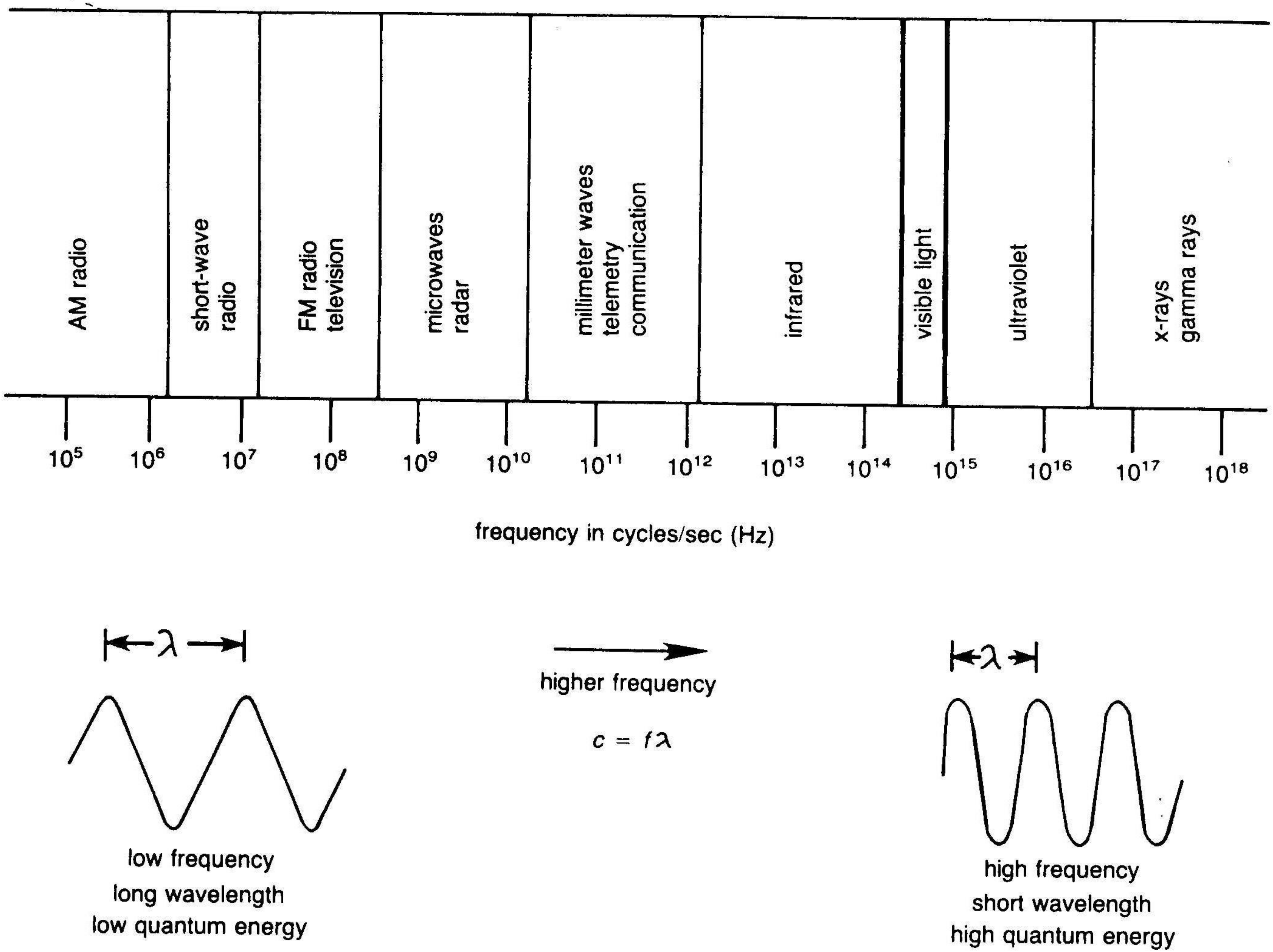
When they travel through a material medium, their effective speed will be less than the free-space speed, but there is no apparent movement of the particles of the medium to mark their passage.



By convention, the EM spectrum is divided into several bands, which lists them in order of increasing frequency. The carrier waves for AM radio signals start at a frequency of about 5×10^5 Hz (λ=600 m).

The center of the visible light region corresponds to $\lambda = 6 \times 10^{-7}$ m or 6000 A, and gamma rays may have $\lambda < 1$ A.

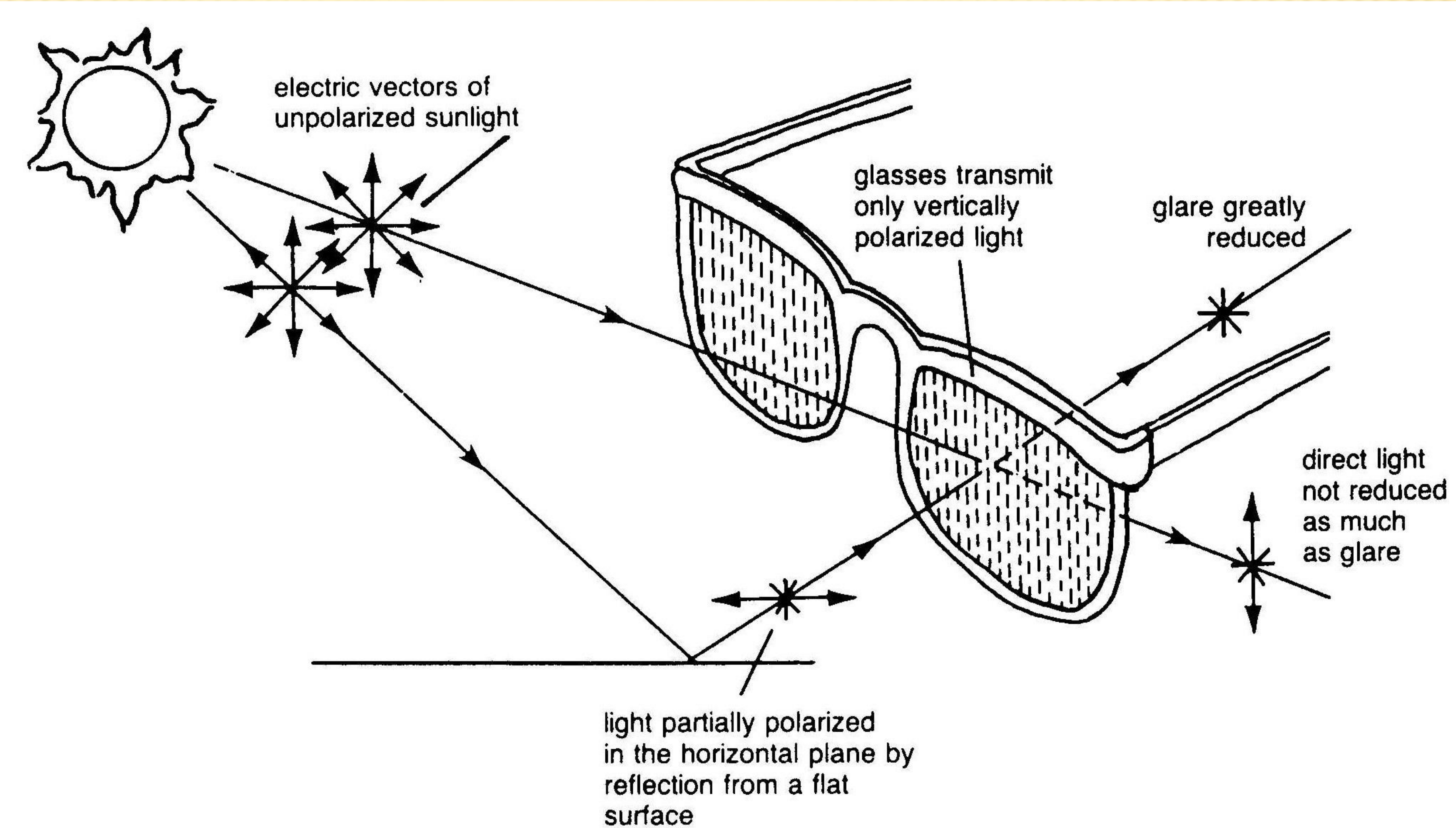
The fact that light can be polarized is evidence of its wave nature. Light is said to be plane polarized if all its electric field vectors are in one plane in space.


AM radio
short-wave radio
FM radio television
microwaves radar
millimeter waves telemetry communication
infrared
visible light
ultraviolet
x-rays gamma rays
10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18}
frequency in cycles/sec (Hz)
λ
higher frequency
$c = f\lambda$
λ
low frequency
long wavelength
low quantum energy
high frequency
short wavelength
high quantum energy

Light from the sun is unpolarized - it contains waves which oscillate in all possible directions $\perp$ to its propagation direction.

When sunlight is reflected from a flat surface (glare), it is partially polarized in the plane parallel to the reflecting surface. This is a horizontal plane for most troublesome glare-producing surfaces (water, beach, roadways, etc.).

Polaroid materials transmit only that light which light vector is polarized parallel to their "pass" direction, so by making Polaroid sunglasses with a vertical "pass" direction, much of the troublesome glare can be eliminated.


electric vectors of
unpolarized sunlight
glasses transmit
only vertically
polarized light
glare greatly
reduced
direct light
not reduced
as much
as glare
light partially polarized
in the horizontal plane by
reflection from a flat
surface

THE QUANTUM THEORY OF LIGHT

From the Middle Ages up through the 19th century there was a continuing debate concerning the nature of light:

- was it composed of waves, or
- was it a stream of tiny particles which emanated from the luminous object?

At the beginning of the 20th century the wave theory had the upper hand.

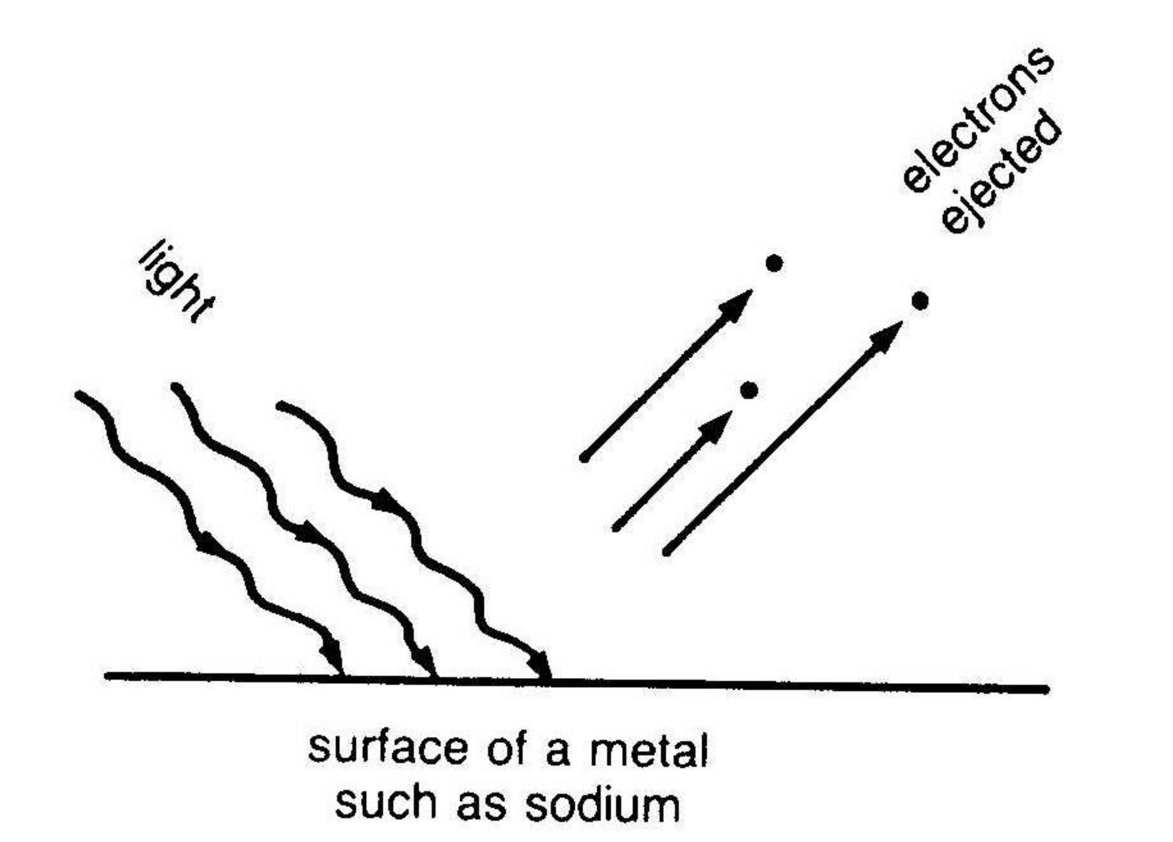
Then, new evidence was found which demonstrated that light exhibits particle properties in interactions on the atomic scale.

One of the most important discoveries was the photoelectric effect.

When light falls on the surface of metals like Na and K, electrons are ejected from the surface, indicating that the energy of the light is given to the electrons to enable them to escape the forces holding them in the metal.

This is not so extraordinary in itself, and at first glance it might seem that the wave theory of light could explain it, since waves carry energy.

But further analysis leads to the conclusion that the light falling on the metal is exhibiting particle properties.



In the attempt to explain the experiment using the wave theory of light, several difficulties arise.

1 . Waves would tend to distribute the energy uniformly in the surface of the metal and it would be extremely unlikely that any single electron would get enough energy to escape from the surface.

Since metals normally must get very hot before electrons escape, it would be expected that a considerable time lag would be observed before even localized heating would give any electron the energy necessary to escape the surface.

Yet these electrons are ejected instantaneously.

2. It would be expected that increasing the intensity of the light would increase the speed of the escaping electrons, since more energy is being given to the metal.

Experimentally the effect of increased light intensity is to increase the number of the electrons ejected, but the maximum velocity stays the same.

This indicates that the light beam consists of a stream of particles with the same energy which collide with electrons and knock them out of the surface.

A more intense beam implies more particles, but the same energy available in a single collision.

3. The frequency of the light would not be expected to have any effect on the experiment.

It is found that changing the color of the light toward blue (increasing f) increases the maximum speed of the ejected electrons. Hence, the light beam consists of particles but the energy of the particles increases with the frequency of the light.

Change in experiment	Change in number of electrons	Change in maximum velocity of electrons
Make light more intense (increase number of photons)	INCREASE	NO CHANGE
Increase frequency of light (increase radiant energy of photons)	NO CHANGE	INCREASE
Make light less intense but of higher frequency (decrease number, but increase energy of photons)	DECREASE	INCREASE

This experiment led to the formulation of the QUANTUM THEORY OF LIGHT.

Light is postulated to exist in the form of quanta called *photons*, each of which has a definite amount of energy.

It is not the equivalent of visualizing a light beam as millions of tiny billiard balls traveling through space. Light has no mass (i.e. no rest mass) and cannot be stopped and localized at a particular point.

But the energy is quantized and the light beam can be visualized as tiny packets of energy traveling through space with $v = 3 \times 10^8$ m/s.

The energy of a photon: $\boxed{E = hf}$ $h = 6.63 \times 10^{-34}$ m^2kg/s.

Hence, a photon of **blue light** has more energy than a photon of **red light.** Light photons are more energetic than microwave or radio wave photons, and X-ray photons are more energetic than those of visible light.

The quantum theory of light explains all aspects of the photoelectric-effect experiment.

The maximum kinetic energy given to the ejected electrons follows the relation $\boxed{E_{max}=hf-W}$ where W - the minimum amount of work required to remove an electron from the metal surface.

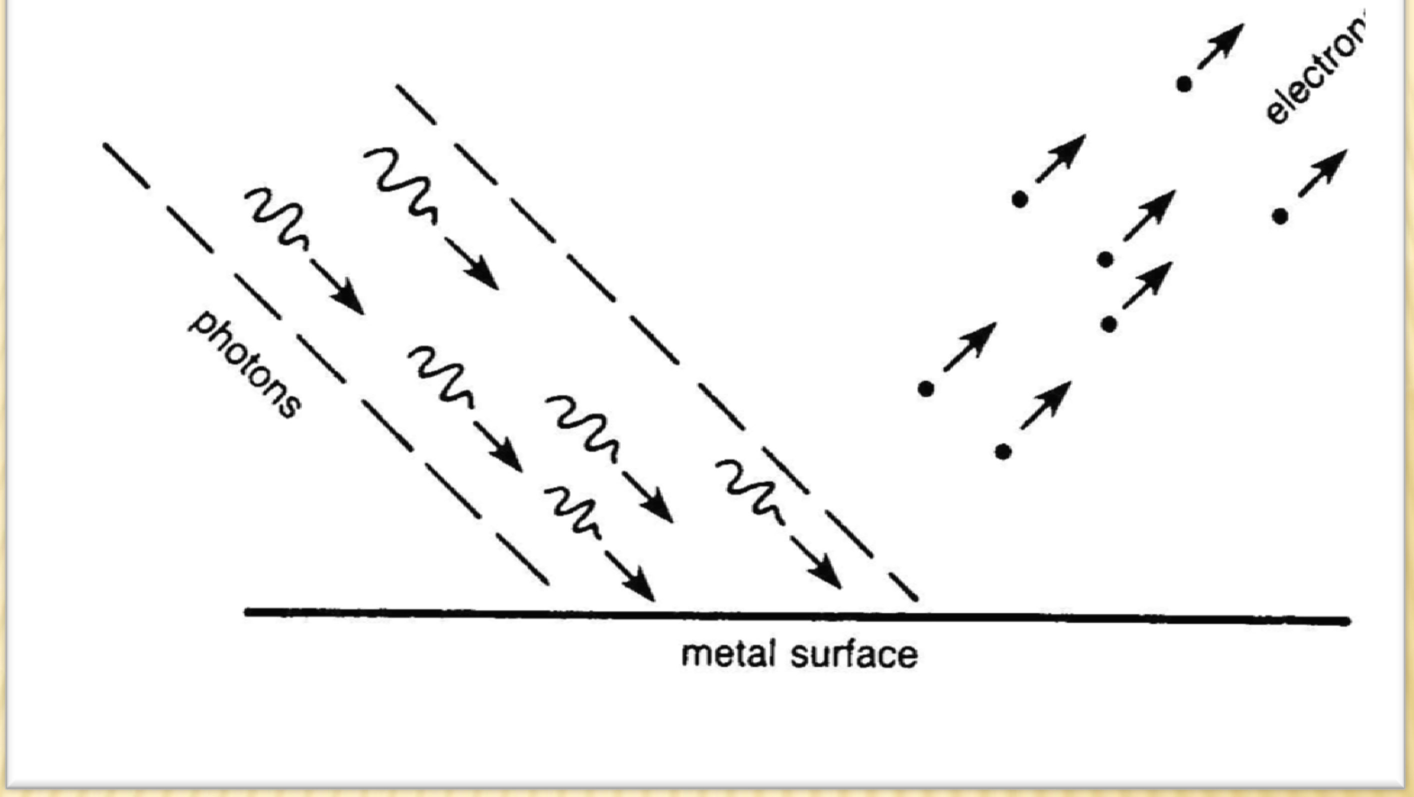
The maximal speed electrons are emitted from the surface of the metal, and electrons with a continuous range of energies below this maximum are emitted, implying that they were deeper in the metal and lost more of their energy in the process of escaping.

The wave/particle dual nature of light is an example of the different frameworks necessary to describe large-scale, ordinary phenomena of classical physics and the small-scale molecular, atomic, and nuclear phenomena.

There's no essential contradiction between quantum physics and classical physics; the laws of classical physics are appropriate only for large-scale phenomena.

If the laws of quantum physics are extended to apply to large-scale phenomena, they produce agreement with the classical physics, but involve a great deal more mathematical complexity.

The wave/particle dual nature of light can be made more comprehensible by the "**wave packet**" model - a photon is visualized as a packet of energy which has some wave characteristics but which is localized in space to the extent necessary to show particle-like properties.



The localization of the photon makes it possible for the total energy of the photon to be transferred to a single electron in an interaction like a particle-particle collision.

When a large number of photons interact at the same time, the individual photon effects are not evident and the total effect is determined by the wavelength, giving the light an essentially wave-like nature.

MATTER WAVES: THE ELECTRON MICROSCOPE

Louis de Broglie suggested in 1923 that the things which we had always regarded as particles might also have a dual nature and exhibit wave properties under the appropriate circumstances.

If duality is a fundamental part of nature, then the electrons might have wave properties.

De Broglie predicted that a particle of mass *m* moving with a velocity v would demonstrate a wavelength

$$\lambda = \frac{h}{mv}$$

The proposed wave nature of the electron would imply that a beam of electrons could be refracted, reflected and focused to form an image.

The confirmation of the wave properties of electrons was made in 1927 by scattering electrons from metal crystals. Findings: the electrons reflected very strongly at certain special angles and not at others.

This behavior could be explained only by invoking wave properties, and the angles were consistent with the wavelength proposed by de Broglie.

Since then other particles such as protons and neutrons have been shown to exhibit such wave properties.

The wave properties of larger objects are not observable because the wavelengths are so small compared to the sizes of the objects.

E.g. The wavelength associated with a 0.15 kg baseball thrown with 40 m/s would be much too small to be observable.

For subatomic particles, however, the wave properties often have profound effects.

If an electron is traveling at a speed of 6×10^6 m/s, the speed it would attain by being accelerated by V=100 V, its wavelength would be $\lambda=1.2 \times 10^{-10}$ m. This is 1.2 A, compared to about 3900 A for the shortest wavelength of visible light ($m_e=9 \times 10^{-31}$kg; $h=6.62607 \times 10^{-34}$ m^2kg/s).

Since the smallest resolvable object is comparable in size to the λ of the radiation used to view it, this example implies that electrons can be used to view much smaller objects.

Since the electron wavelength decreases with increasing electron speed, the resolution can be further improved by using higher speed electrons.

In the *electron microscope,* electrons are used to form images in a way analogous to that of a projecting light microscope.

A high energy electron beam is produced by an electron gun similar in principle to that in the oscilloscope.

Magnetic fields are used to focus the electrons.

The final image is formed on a fluorescent screen, which produces visible light when struck by the high speed electrons, or it is recorded on photographic film.

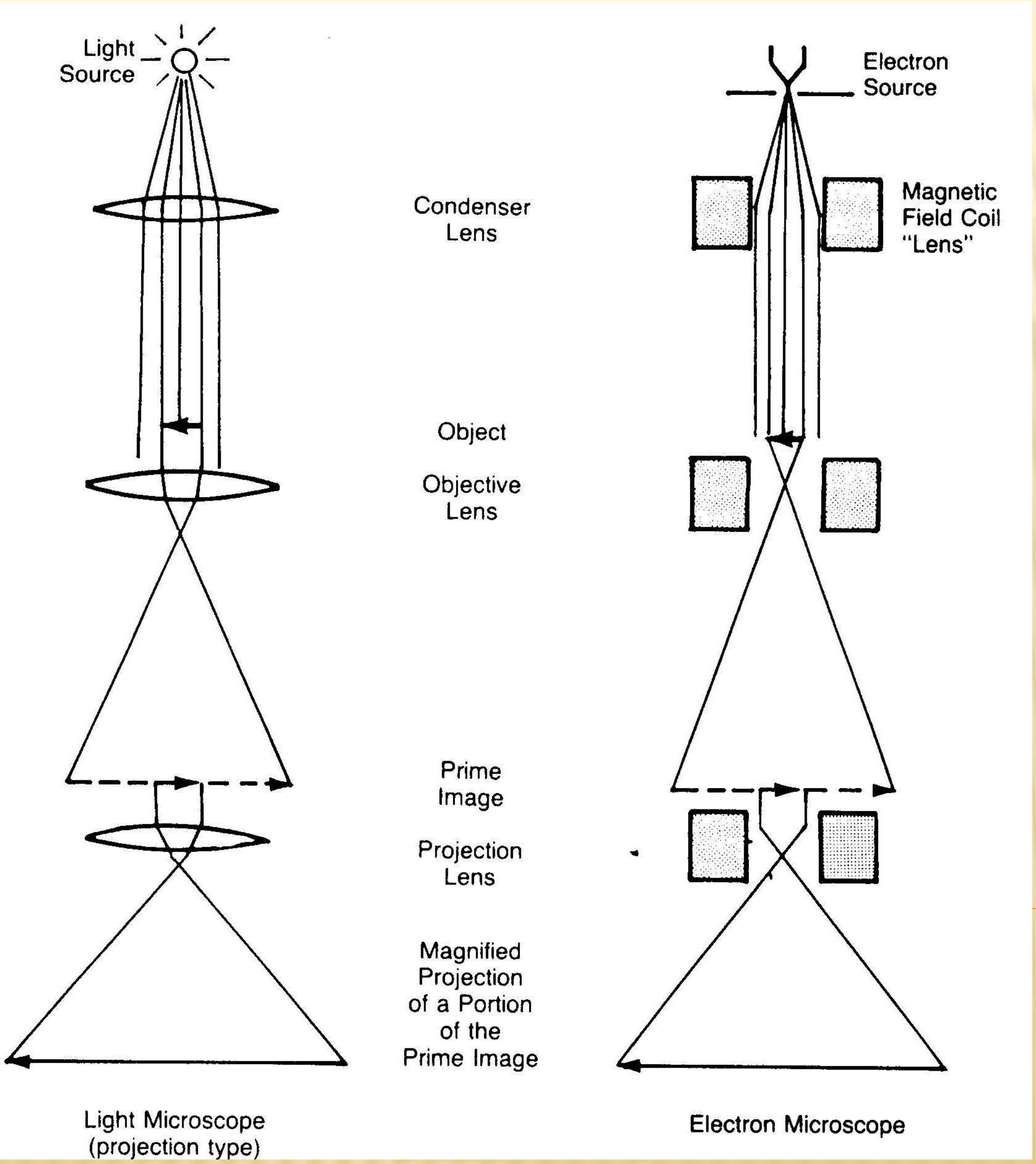
There is a theoretical limit on the resolution of an optical microscope - objects significantly smaller than the wavelength of light cannot be observed. Even with special techniques the limit of resolution is around 2000 A.

With the commonly used voltage of 50 kV on the electron gun, the e^- in the electron microscope have $\lambda=0.08$ A.

Because of limitations on the magnetic "lenses" which focus the electrons, the actual limit of resolution is about 10 A.

The large improvement in resolution makes the electron microscope an invaluable tool for biomedical applications.

It can be used for observing small organisms such as viruses and for the observation of the structural details of cells which are too small for observation with optical microscope.


Light Source
Electron Source
Condenser Lens
Magnetic Field Coil "Lens"
Object
Objective Lens
Prime Image
Projection Lens
Magnified Projection of a Portion of the Prime Image
Light Microscope (projection type)
Electron Microscope

THE INTERACTION OF EM WAVES WITH MATTER

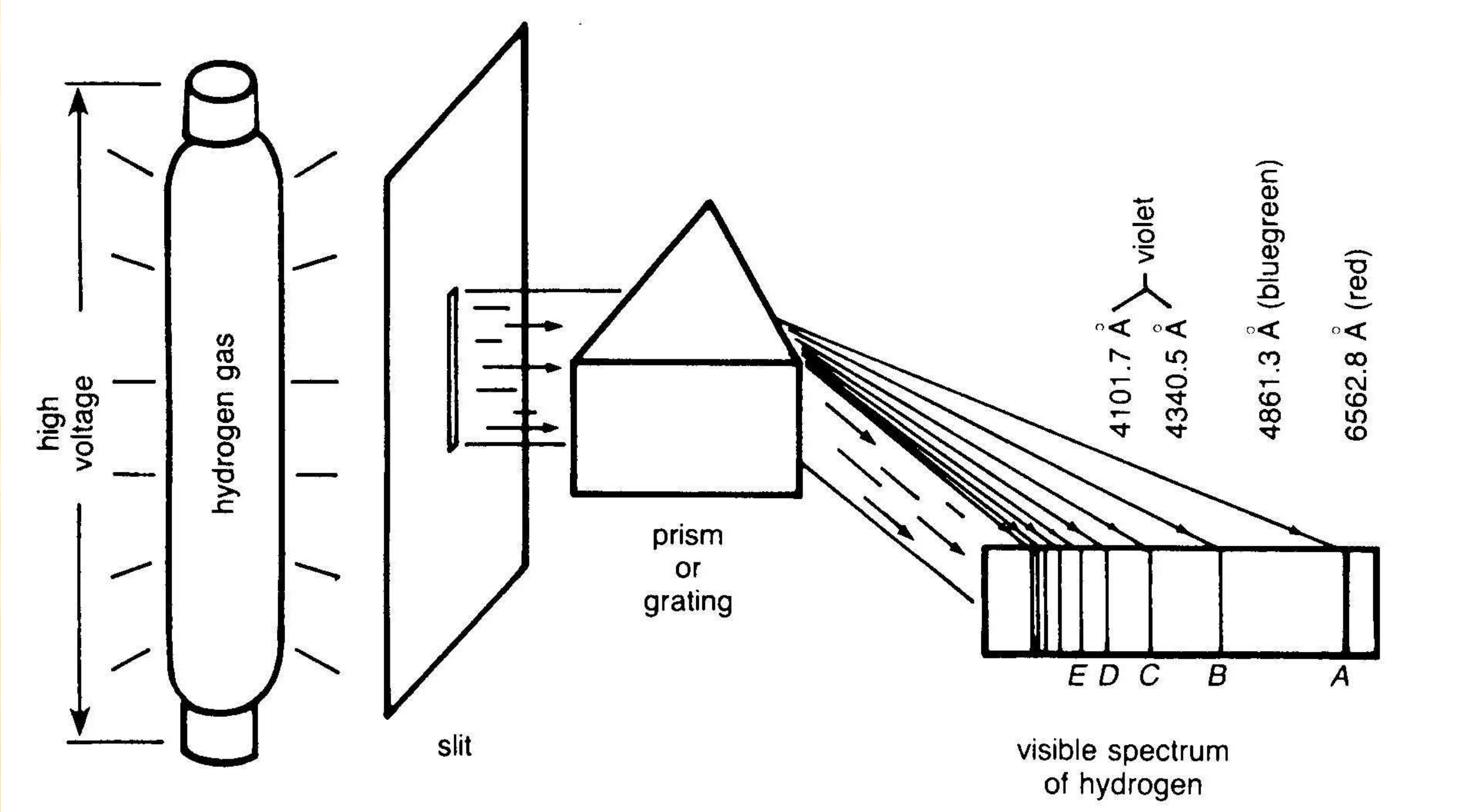
The study of selective absorption or emission of electromagnetic waves is known as **spectroscopy**.

The emission spectrum of hydrogen is one of the most thoroughly studied examples. If hydrogen gas is placed in a sealed glass container and subjected to a high voltage, it will emit pink light along the electrical discharge path and usually emits blue light in other parts of the container.

If this light is passed through a diffraction grating to separate the colors, the spectrum will appear as a series of bright lines of different colors.

In contrast to the continuous distribution of colors obtained by passing white light through a prism, only certain discrete colors (f) are emitted by the hydrogen.

These frequencies are determined by the quantized energy levels which the hydrogen electron can occupy.

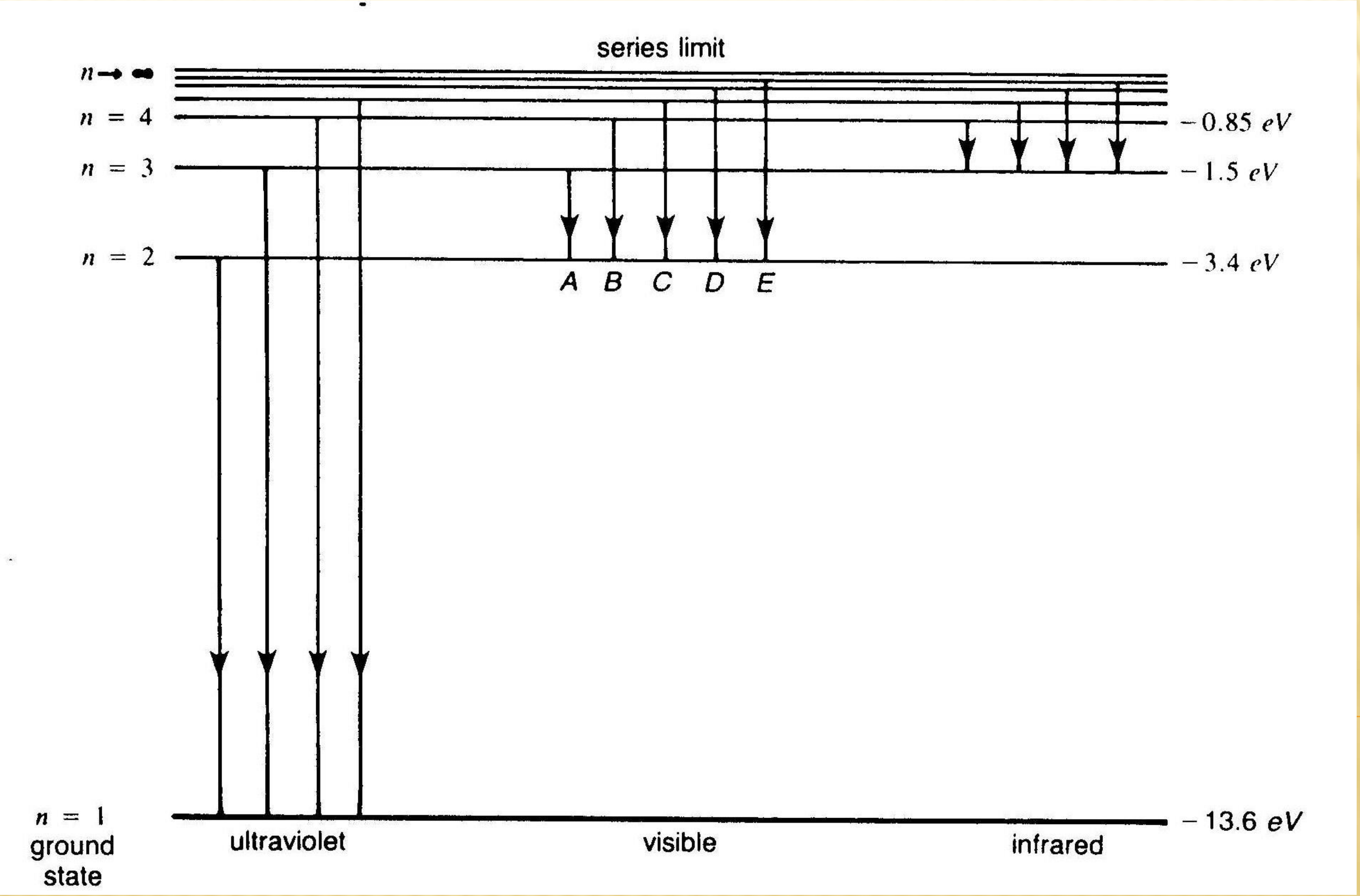


The hydrogen e^- normally occupies the first shell (n =1). If it receives energy from an electrical discharge it can jump up to any one of the higher levels. The n= 1 level is referred to as the "**ground state**" for the electron and the higher states are called "**excited states**."

After excitation, the e^- has a strong tendency to drop down to one of the lower states, continuing the process until it reaches the ground state. In order to drop to a lower state, it must give off energy (the conservation of energy principle).

This energy is given off in the form of a photon, a quantum of light. The frequency (color) of light given off is determined by

$$\Delta E = E_{initial} - E_{final} = hf.$$

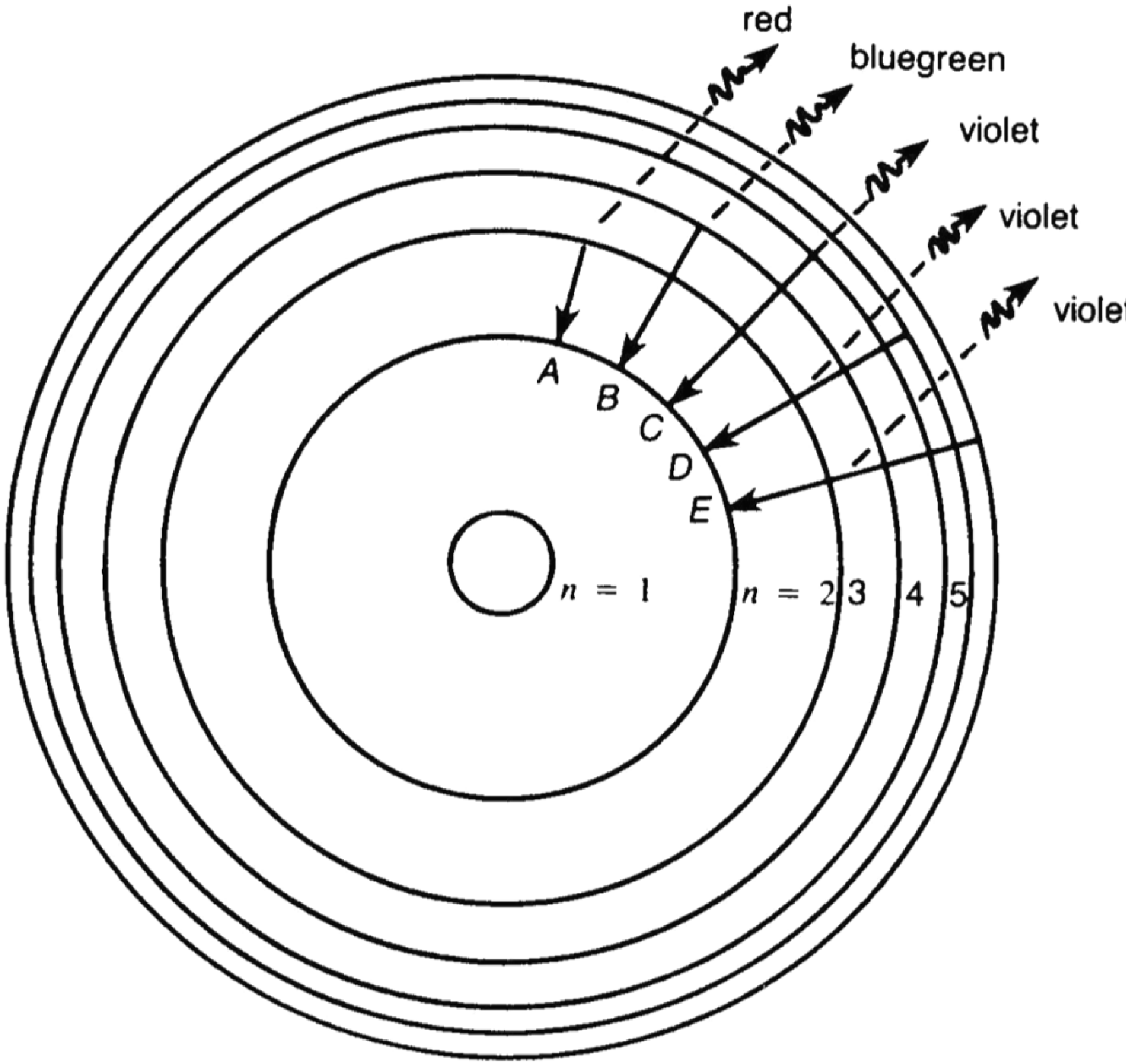

series limit
$n \to \infty$
$n = 4$
$n = 3$
$n = 2$
$n = 1$
ground state
− 0.85 eV
− 1.5 eV
− 3.4 eV
− 13.6 eV
A B C D E
ultraviolet
visible
infrared

red	700-635 nm
orange	635-590 nm
yellow	590-560 nm
green	560-490 nm
blue	490-450 nm

A larger difference between energy levels will produce radiation at a higher frequency. The energy level separation associated with transition A is such that the emitted light is red (ΔE=1.8889 eV).

Since the spectra can be measured very accurately, it is recommended to use physical constants with an accuracy of about five significant digits.

Using the wave relationship $c = f\lambda$, the wavelength is λ=6564 A. This is extremely close to experimentally measured wavelength 6562.8 A. The small deviation may be attributable to small inaccuracies in the constants used, neglect of the motion of the nucleus, and other small effects.


red
bluegreen
violet
violet
violet
A
B
C
D
E
n = 1
n = 2
3
4
5

Other transitions produce ultraviolet, infrared, or other frequencies, outside the sensitive range of the human eye.

The frequencies of the spectral lines for a given element are unique and precisely reproducible. Each element has a characteristic set of allowed energy levels for the electrons.

The spectral lines can be used to identify the element emitting them, even when they are mixed with spectra from many other elements.

E.g. the discovery of a red spectral line at λ= 6562.8 A would indicate the presence of hydrogen. A check for the presence of the other known wavelengths in the hydrogen spectrum would provide a positive demonstration of the presence of hydrogen.

Such "fingerprints" from an emission spectrum may be used in spectrochemical analysis to check for the presence of trace quantities of toxic elements such as arsenic or lead.

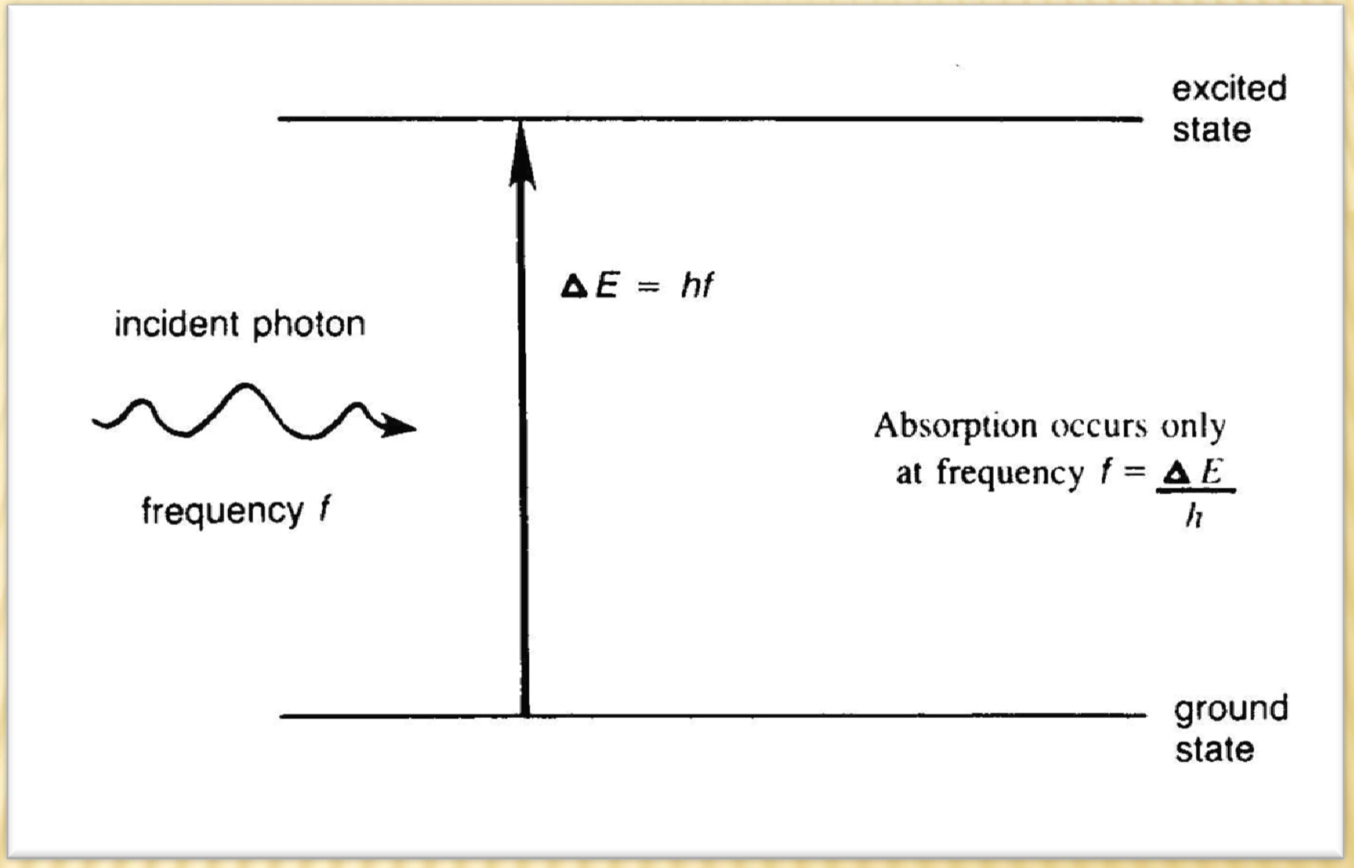
If white light is passed through cool hydrogen gas and then passed through a diffraction grating, the result will be dark bands superimposed upon the continuous rainbow spectrum characteristic of the white light.

These dark bands are associated with absorption of light by the cool gas and will occur at the same wavelengths as the bright lines of the emission spectrum of hydrogen.

Since the e^- can exist only in specific energy states, only those photons with energies equal to the separation between allowed energy states can be absorbed. $\Delta E = hf$.

An example of absorption spectroscopy is the identification of the chemical elements present in stars. If the light from the sun or another star is passed through a grating, the result is a continuous spectrum with superimposed dark bands corresponding to the absorption of light by the cooler gases surrounding the star.

From wavelength measurements the chemical elements can be identified, even across the vast distances of space.



The atoms and molecules of solid objects interact with each other and produce many more allowed energy levels which merge into continuous bands of possible energy levels.

The energy bands of a solid object may offer a continuum of levels such that any frequency in the visible range will be absorbed, causing that object to be opaque to visible light.

It may, however, be transparent to x-rays or other frequencies for which there are no corresponding energy level separations in the material.

The colors of solid objects are often the result of selective absorption. The nature of a green object is such that it absorbs all of the visible spectrum except green, which is reflected to provide the perceived color.

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