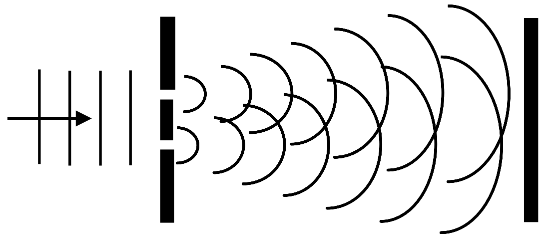
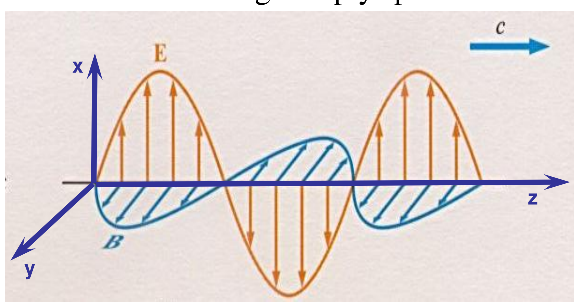
THE PARTICLE NATURE OF LIGHT

1. In the previous lecture I gave you some very strong reasons to believe that light is waves. Else, it is impossible to explain the interference and diffraction phenomena that we see in innumerable situations. Interference from two slits produces the characteristic pattern.

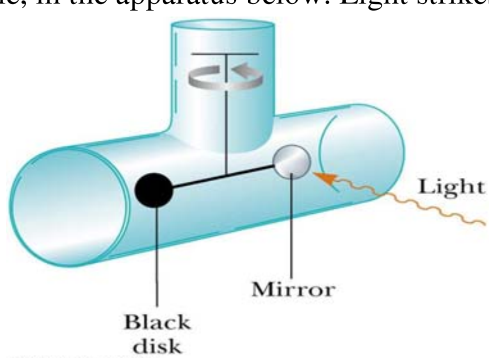


2. Light is waves, but waves in what? of what? The thought that there is some invisible medium (given the name *aether*) turned out to be wrong. Light is actually electric and magnetic waves that can travel through empty space. The electric and magnetic waves



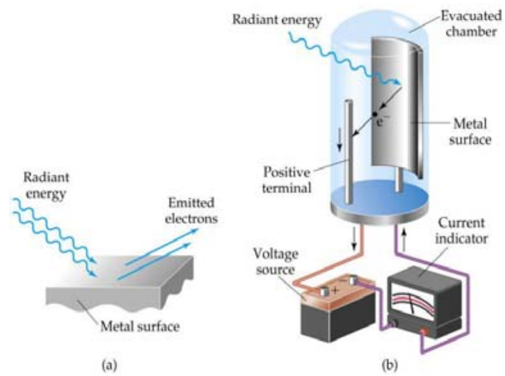
are perpendicular to each other and to the direction of travel (here the z direction).

3. Electromagnetic waves transport linear momentum and energy. If the energy per unit volume in a wave is U then it is carrying momentum p, where $p = U/c$. Waves with large amplitude carry more energy and momentum. For the sun's light on earth the momentum is rather small (although it is very large close to or inside the sun). Nevertheless, it is easily measureable as, for example, in the apparatus below. Light strikes a mirror and rebounds.



Thus the momentum of the light changes and this creates a force that rotates the mirror. The force is quite small - just 5×10^{-6} Newtons per unit area (in metre^2) of the mirror.

4. So strong was the evidence of light as waves that observation of the photoelectric effect came as a big shock to everybody. In the diagram below, light hits a metal surface and

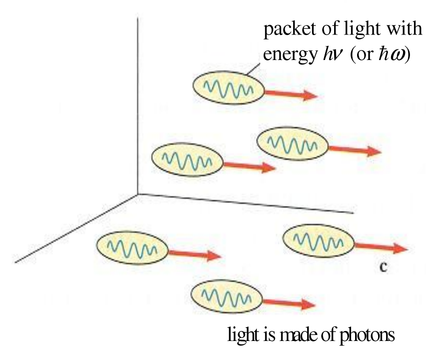


and knocks out electrons that travel to the anode. A current flows only as long as the light is shining. Above the threshold frequency, the number of electrons ejected depends on the intensity of the light. This was called the photoelectric effect. The following was observed:

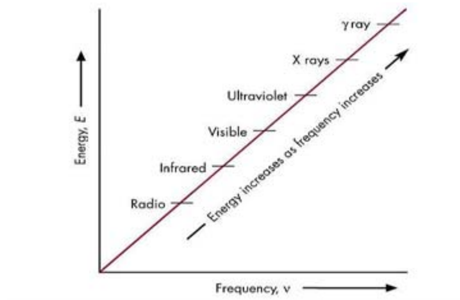
a) The photoelectric effect does not occur for all frequencies ν; it does not occur at all when ν is below a certain value. *But classically (meaning according to the Maxwell nature of light as an electromagnetic wave) electrons should be ejected at any ν. If an electron is shaken violently enough by the wave, it should surely be ejected!*

b) It is observed that the first photoelectrons are emitted instantaneously. *But classically the first photoelectrons should be emitted some time after the light first strikes the surface and excites its atoms enough to cause ionization of their electrons.*

5. Explanation of the photoelectric puzzle came from Einstein, for which he got the Nobel Prize in 1905. Einstein proposed that the light striking the surface was actually made of little packets (called quanta in plural, quantum in singular). Each quantum has an energy energy $\varepsilon = h\nu$ (or $\varepsilon = \hbar\omega$ where $\hbar = h/2\pi$ and $\omega = 2\pi\nu$) where h is the famous Planck's constant, 6.626×10^{-34} Joule-seconds. An electron is kicked out of the metal only when a quantum has energy (and frequency) big enough to do the job. It doesn't matter how many quanta of light - called photons - are fired at the metal. No photoelectrons will be released unless ν is large enough. Furthermore the photoelectrons are released immediately when the photon hits an electron.

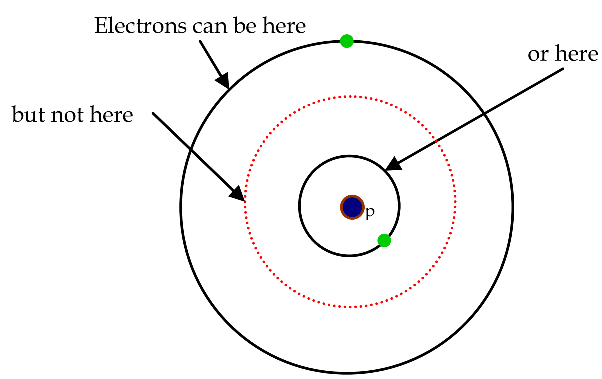


6. Microwaves, radio and TV waves, X-rays, γ-rays, etc. are all photons but of very different frequencies. Because Planck's constant h is an extremely small number, the energy of each photon is very small.

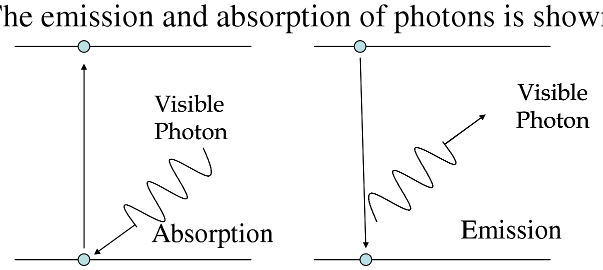


7. How many photons do we see? Here is a table that gives us some interesting numbers:
   a) Sunny day (outdoors): 10^{15} photons per second enter eye (2 mm pupil).
   b) Moonlit night (outdoors): 5×10^{10} photons/sec (6 mm pupil).
   c) Moonless night (clear, starry sky): 10^{8} photons/sec (6 mm pupil).
   d) Light from dimmest naked eye star (mag 6.5): 1000 photons/sec entering eye.

8. Where do photons come from? For this it is necessary to first understand that electrons inside an atom can only be in certain definite energy states. When an electron drops from a state with higher energy to one with lower energy, a photon is released whose energy is exactly equal to the difference of energies. Similarly a photon is absorbed when a photon of just the right energy hits an electron in the lower state and knocks it into a higher state.

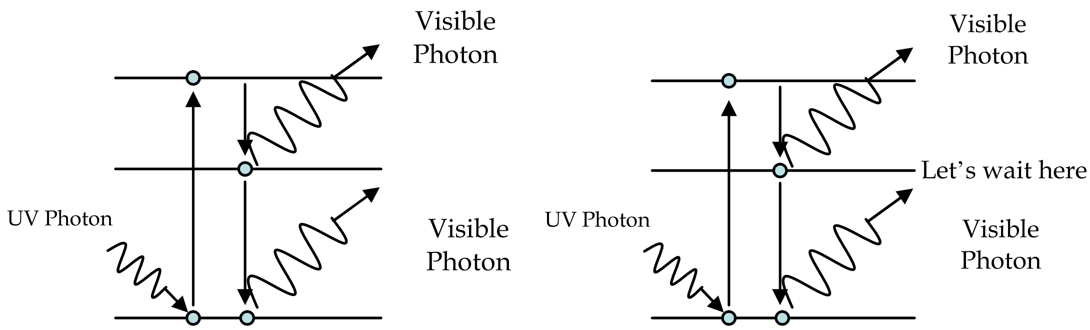


The upper and lower levels can be represented differently with the vertical direction representing energy. The emission and absorption of photons is shown below.



9. Fluorescence and phosphorence are two phenomena observed in some materials. When they are exposed to a source of light of a particular colour, they continue to emit light of a different colour even after the source has been turned off. So these materials can be

seen to glow even in the dark. In phosphorescence, a high-frequency photon raises an electron to an excited state. The electron jumps to an intermediate states, and then drops after a little while to the ground state. This is fluorescence. Phosphorescence is similar to fluorescence, except that phosphorescence materials continue to give off a secondary glow long (seconds to hours) after the initial illumination that excited the atoms.



10. One of the most important inventions of the 20th century is the laser which is short for:

LASER ≡ **L**ight **A**mplification by the **S**timulated **E**mission of **R**adiation

Lasers are important because they emit a very large number of photons all with one single frequency. How is this done? By some means - called optical pumping - atoms are excited to a high energy level. When one atom starts decaying to the lower state, it encourages all the others to decay as well. This is called spontaneous emission of radiation.

QUESTIONS AND EXERCISES

Q.1 With reference to the diagram in point no. 3, suppose that light illuminates both the mirror and the darkened plate. On which will the force be greater? To answer this, ask on which plate is the change of momentum greater and then relate this to Newton's Law which states that force is rate of change of momentum.

Q.2 In order to remove an electron from a certain metal, it is necessary to give at least 2.2 eV energy to the electron. What should be the minimum frequency of a beam of light to ensure that photoelectrons are emitted? What if the frequency is larger than this? Where will the energy go?

Q.3 A laser pulse of green light at 550 nm puts out 2 joules of energy in 1 millisecond. How many photons does the pulse have? What if it is blue light?