

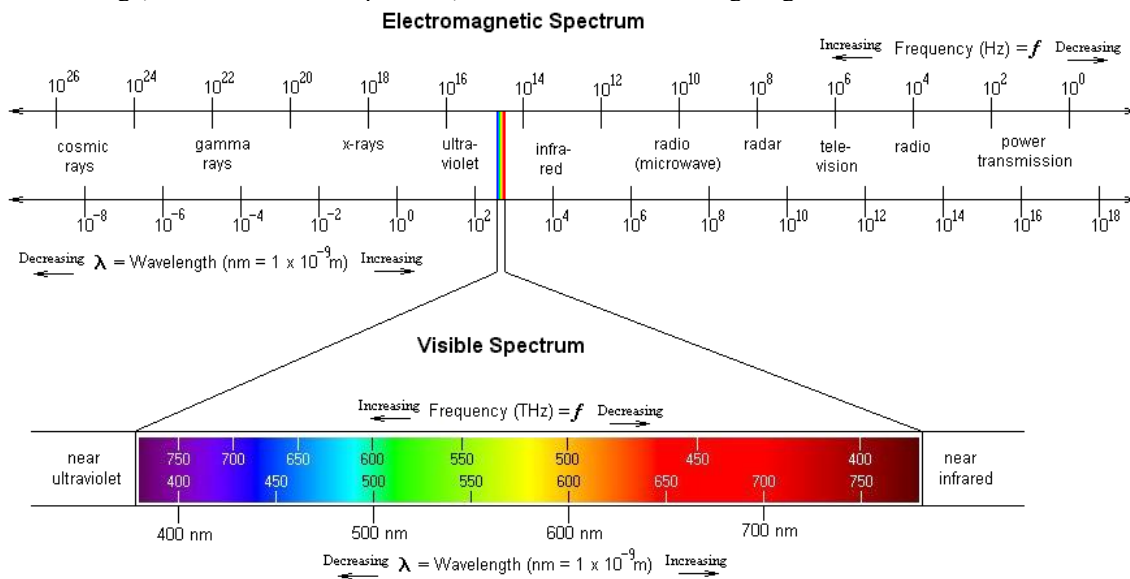
## Lesson 90 – Electromagnetic Spectrum

The electromagnetic spectrum is a continuum. We know of no limits. Electromagnetic radiation can, apparently, exhibit all imaginable wavelengths, frequencies and energies. Yet, each photon can have only one energy, one wavelength and one frequency. The diagram below shows that part of the electromagnetic spectrum still being explored by current science. PLEASE NOTE that this diagram is swapped left for right when compared with the diagram in the textbook.

Charged particles, like electrons, or dipolar molecules, like water, or any object with moving charges within it, like electrical wiring in your home, can receive energy from their surrounding and loose energy to their surroundings by absorbing and emitting electromagnetic energy. That is, they absorb and emit light. The light may be visible or invisible. Most of the light in the universe is, in fact, invisible.

Since electrons in atoms may occupy only certain energy levels, those electrons can only emit or absorb certain frequencies of light. The energy in the light they emit and absorb are sometimes called quanta; a reference to the quantized nature of the energy levels the electrons occupy.

The electromagnetic spectrum as we know it encompasses energy transitions over a very wide range of energies, frequencies and wavelengths. The light that is visible to human eyes occurs only in a very narrow range, called the Visible Spectrum, as shown in the following diagram.



The narrow range of visible light wavelengths extends from about 400 nanometers to about 750 nanometers. The narrow range of visible frequencies extends from about 400 terahertz to about 750 terahertz.

When using terms like wavelength and frequency we are merely reporting on the wavelike properties of the light. However, these quanta or photons also carry energy. The relationship between frequency or wavelength, and energy is

$$E = h f = hc/\lambda$$

Where  $h$  is a universal constant known as Planck's constant ( $h = 6.626 \times 10^{-34} \text{ J}\cdot\text{s} = 4.136 \times 10^{-15} \text{ eV}\cdot\text{s}$ ). In terms of the energy carried by a single photon or quantum, then, the range of visible light extends from about  $2.6 \times 10^{-19} \text{ J}$  to about  $5.0 \times 10^{-19} \text{ J}$  or from about 1.65 eV to about 3.10 eV.

For light quanta in the infrared range, lower frequencies and longer wavelengths, the energy per quantum is less than for quanta in the visible range. For light quanta in the ultraviolet range, higher frequencies and shorter wavelengths, the energy per quantum is higher than for quanta in the visible range. In other words, higher energies are on the left side of this diagram and lower energies on the right side of this diagram.

Electromagnetic radiation consists of alternating, mutually-supporting electric and magnetic fields. The changing electric field creates a changing magnetic field. The changing magnetic field creates a changing electric field. These two fields thus continuously recreate each other. They constitute a moving ripple in space. The ripple of these mutually-supporting fields travels through space at the speed of light.

Electromagnetic radiation consists of these two fields moving through space. It also carries energy. Its particle-like properties are evident from the fact that particles as small as electrons, the smallest objects known to modern science, can absorb the energy contained in these particles, called photons.

The wave-like property of electromagnetic radiation can be demonstrated in many ways. Perhaps none is as simple as that obtained by shining light through groups of parallel slits or through a diffraction grating.

The particle-like and wave-like properties of light are not mutually exclusive. They are both essential characteristics of the phenomenon we call light.

### Interactions of Light and Matter

Light can only exchange energy with matter that also has a changing electric field, a changing magnetic field, or, most typically, both. In addition, the changing electric field, let's say, must be changing at exactly the same frequency in the molecule as in the light. When the photon and the matter achieve this resonance, they may exchange energy. Whether they will or not is a matter of probability. Interactions between light and matter are a lot like rolling dice or tossing coins.

When light of the proper frequency passes through a medium capable of absorbing it, there is a certain probability of a photon being absorbed in the first centimeter of travel. During the next centimeter of travel through the medium the photon's probability of being absorbed is the same as it was during the first centimeter. We have seen this constant probability situation before. This is another case of exponential behavior in nature.

We report light levels in terms of Intensity,  $I$ . For light whose initial intensity is  $I_0$ , we can write its intensity as a function of distance traveled through the medium as

$$I(\ell) = I_0 e^{-k\ell}$$

Or

$$-\ln(I / I_0) = k\ell$$

where  $k$  is a constant that depends on the properties of the absorbing medium and  $\ell$  is the path length of the light through the medium.

The ratio  $(I / I_0)$  is the fraction of the light transmitted through the medium without being absorbed. This ratio is sometimes referred to simply as the transmittance. Multiplying this ratio by 100% gives us the percent transmittance.

$$T = (I / I_0)$$

$$\%T = (I / I_0) \times 100\%$$

The ratio  $(I / I_0)$  is also the probability of a given photon getting through the medium without being absorbed. Various kinds of detectors can be used to measure the intensity of the light before it enters the medium and again after it has traveled through the medium. The primary job of a spectrophotometer is to measure this ratio,  $(I / I_0)$ .

We define the absorbance of the medium as  $A = -\ln (I / I_0) = k \ell$ .

This provides the mathematical connection with Lambert's Law. Lambert showed, by using thicker and thicker pieces of otherwise identical glass, that the absorbance is proportional to the path length. In other words, that

$$A = k \ell.$$

Most spectrophotometers will convert the intensity ratio to absorbance, automatically, if you wish.

When we consider the case of absorbance by metal ion salts dissolved in a solvent we introduce a new variable into our considerations; namely the concentration of the dissolved metal ions. Beer investigated this system. He found that for a given concentration of the metal ion, Lambert's Law still holds. When Beer started changing the concentration of the metal ion he found that he had to replace the  $k$  in Lambert's Law with a new one. He found, at low concentrations of metal ions, what we now call Beer's Law; namely,

$$A = \epsilon \ell C$$

Where,  $A$  is still absorbance  $= -\ln (I / I_0)$ ,  $\epsilon$  is a new constant characteristic of the metal ion in a particular solvent,  $\ell$  is still the path length, and  $C$  is the concentration of the metal ions in the solution. When the concentration  $C$  is measured in moles per liter and the path length  $\ell$  is measured in centimeters,  $\epsilon$  is called the molar extinction coefficient or the molar absorptivity. The molar absorptivity varies with the wavelength of the light so it is customary to report  $\epsilon$  only at the important peaks of maximum absorbance in the solution. These peaks in absorbance occur at wavelengths where the metal ion and the light interact most strongly. They mark the wavelengths where light is being absorbed by the metal ion. In other words, they tell us something about the energy states available to absorb energy within the metal ion. Spectroscopic studies suggested by such considerations marked the beginning of our detailed understanding of the inner structure of the atom. That in turn created the need for Quantum Mechanics and the rest is history.