2.2: The Particle Nature of Light

Learning Objectives

You will be able to perform calculations and understand conceptually the relationship between energy and frequency

What Do You Think: Wavelength and Frequency

The same group of students continues on the next part of their homework; they are soon joined by another group, who are arguing over the correct answers.

- **Ting-li:** Hey all. We're having a debate about the homework, can you help us decide who's right?
- **Sasha:** We can try—what's the problem?
- **Ting-li:** Well, Uhura and I think that the longest wavelength light—radio waves —has the most energy .
- **Uhura:** It just makes sense, if one thing is bigger, so is the other. Vanessa thinks we're wrong. What do you think?
- **Sasha:** Oh, we just talked about that. Remember the equation for energy uses frequency , not wavelength. So if frequency is bigger, so is the energy.
- **Piper:** And frequency and wavelength are opposite each other. That means that big wavelengths have small frequencies, which means small energies.
- **Vanessa:** Right, like I said, the most energetic light is whatever has the highest frequency and shortest wavelength. Like gamma rays .

Do you agree with any of these students and if so, whom?

Piper

Sasha

Ting-li

Uhura

Vanessa

None

Explain

There is another way to describe light in addition to electromagnetic waves. In some cases, light behaves more like particles. Toward the end of the 19th century, Heinrich Hertz first observed that when a metal is exposed to light, it will absorb energy from the light and emit electrons. In subsequent experiments, physicists found that the amount of energy absorbed by the metal depends on the frequency of the light that is shining on it. This is known as the photoelectric effect. More specifically, the German physicist Max Planck (1858 – 1947) showed that the energy E of light with frequency f is given by the expression below.

$$E = hf$$

where the SI units for energy are joules (J) and the units for frequency are Hz. The constant of proportionality, h, is called **Planck's constant**. It is an extremely small number. In SI units, Planck's constant is 6.626×10^{-34} J s. The equation means that the *higher* the frequency of a photon, the *higher* its energy.

Until this time, models of electromagnetic radiation predicted that the energy of light should depend on its amplitude, or intensity; they could not explain the dependence on frequency. It was Albert Einstein (1879-1955) who clarified the matter when he explained the photoelectric effect. In deducing how the photoelectric effect works, Einstein showed that light can be modeled as discrete little packets, like particles, each having energy hf. More precisely, Einstein showed that light behaves as if it were made of discrete particles when it is absorbed.

Since the energy of a particle of light depends on its frequency, an incoming particle with a high enough frequency will have enough energy to liberate an electron from a metal. The higher the intensity of light shining on a metal, the more packets, or particles, the metal absorbs and the more electrons are emitted. However, if the frequency of the light is too low, then no electrons can be liberated, no matter how many of them are present. This is because no single light particle has the required minimum energy, and these particles are absorbed only one at a time.

In everyday life, the photoelectric effect explains the working of solar panels, for example. Because of the particle nature of light, we can capture the energy of sunlight. In astronomy, we make use of the particle nature of light by using the photoelectric effect to record the number of photons that come from a particular region of the sky. In this way, we can take an image of the sky and determine the brightness of an astronomical object.

Einstein's idea of light as discrete packets of energy was published in 1905. It was not until 21 years later that the chemist Gilbert Lewis published his own theory of particle light (now long abandoned) in which he called these particles of light photons. Though Lewis's theory was inconsistent with many behaviors of light known through experiments, his name for the particles, photons, was adopted immediately and has stuck to this day.

So, now when scientists talk about light, they might refer to electromagnetic waves or photons of a given energy, frequency, or wavelength. All are equivalent. While it can be confusing at first, this is how the nomenclature developed historically. No one has yet come up with a better system. After all, how do you describe something that seems to be both particle and wave, and which can have a wide range of frequencies or wavelengths?

Energy, Frequency, and Wavelength

Using the equations introduced in this and the previous section, calculate the wavelength, frequency, and energy of the light.

Example 2.2.1

A visible light photon has a wavelength of 500 nm (nm is short for nanometer, 10^{-9} m).

1. What is the frequency of this photon?
   - Given: λ = 500E-9 m
   - Find: frequency f
   - Concept(s): λ = c / f where c = 3E8 m/s
   - Solution: (500E-9 m) = (3E8 m/s)/ f
   - f = (3E8 m/s) / (500E-9 m) = 6E14 s^{-1} = 6E14 Hz
2. What is its energy?
   - Given: f = 6E14 Hz
   - Find: energy E
   - Concept(s): $E = hf$ where h = 6.626E-34 J s
   - Solution: E = (6.626E-34 J s) × (6e14 Hz) = 3.98E-19 J

Questions:

1. An ultraviolet photon has a frequency equal to 2.41 x 10^{15} Hz.

a. What is its wavelength?

m

Show your work:

b. What is its energy?

J

2. An x-ray photon has a wavelength of 10^{-11} m.

a. What is it's frequency?

Hz

Show your work:

b. What is its energy?

J

Show your work:

When students first learn about light, they often ask questions like, “So which is light, a particle or a wave?” These questions are understandable, but they miss the point. We cannot really see light (yes, our eyes detect it, but they are not able to measure its properties in detail). We can only measure light’s properties in careful laboratory experiments. In some experiments, light shows wave-like behaviors. That is, it can bend around sharp corners or small obstructions (think of water waves bending around the end of a jetty or around the pilings of a pier). At other times, as in the photoelectric effect, light behaves as if it were a particle. So, which is it really? To answer that question, let us think about what we are doing when we claim it is one or the other.

When we claim that light is a wave, what we are really saying is that it has similar characteristics to certain macroscopic objects (water or waves on a string are examples) that we call waves. Furthermore, we are saying that the same (fairly detailed) mathematical tools we use to describe water waves and waves on strings can be used to describe light. But does that really mean that light is a wave?

A better way to think about it might be that waves are one *model* that we can use to describe light. The model is very good at describing certain aspects of light. For other aspects, like when light is emitted or absorbed by a material, the wave model can fail completely. In that case, we have found that a different model, a particle model, works very well. But the particle model cannot explain the bending of light around edges.

So, light behaves in these two apparently incompatible ways. Does this mean that light is both a particle and a wave? Well, that does not seem to make a lot of sense. Perhaps it is better just to say that light is light. Sometimes it behaves like a wave, and sometimes like a particle; it depends on the experiment you do. What seems clear is that our two models of light, though they work quite well in their separate domains of applicability, fail to give us a fully satisfying picture of the nature of light. This will be a general aspect of many of the models we develop to explain new phenomena: We must generally try to explain new phenomena in terms of ideas already familiar, and those old ideas might be inadequate to fully explain the new cases we come across, at least in ways that make us comfortable.
