Particle or Wave?
Part 2

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Photons in the Spectrum

Even though photons are used when dealing with the light frequency range, we can still refer to a quantum of energy in other frequency bands, such as the radio frequency (RF) or microwave bands, which we call respectively, an “RF Photon” and a “Microwave Photon.”

Because photons of higher frequency carry greater energy, the *particle nature* of light becomes increasingly important as the frequency of radiation increases or as wavelength decreases.

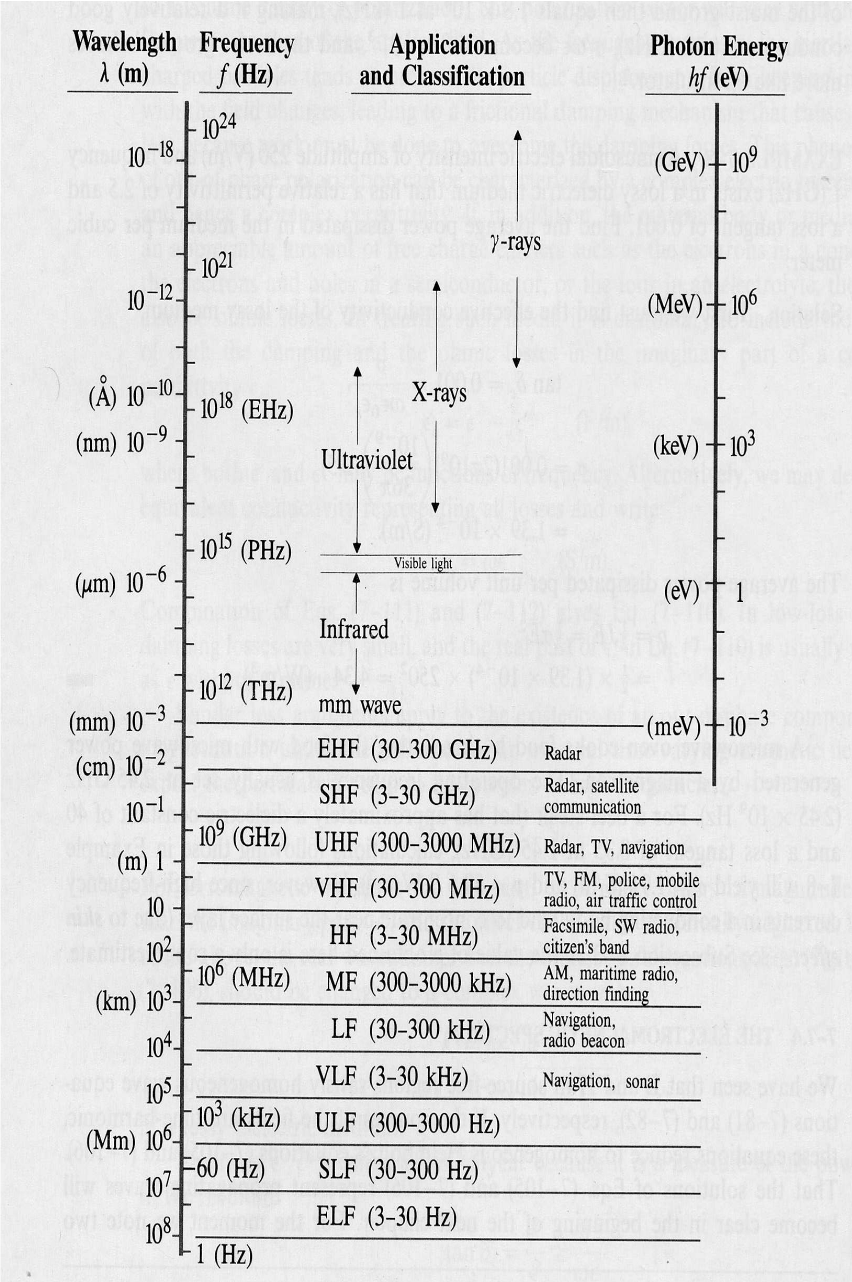
The Figure on the next page shows the electromagnetic spectrum in terms of wavelength and frequency range and briefly delineates their modern applications as well as the scale of photon energy levels.

From this diagram we can see that photons in the lower infra-red range and below have energy levels below 1 electron volt (eV) and are usually considered waves, whereas photons with energy levels in the upper ultra-violet range and above have energy levels in the keV and are usually considered particles.

It is in the visible light range that we have a twilight zone, and a certain degree of confusion; an uncertainty of whether light acts as a particle or wave. This concept is treated in depth in the next article.

"There are two ways of spreading light: to be the candle or the mirror that reflects it."

—Edith Wharton (1862-1937)
American Novelist and Writer



Electromagnetic Spectrum And Scale Of Photons

Particle or Wave?

Using the Heisenberg's uncertainty principle, we can conclude that for large scale phenomena existing on a classical physics level, the uncertainty principle does not pose any serious restrictions on the particle's location, velocity, energy, or time of observation.

On the other hand, for atomic and subatomic particles, the situation is indeterminate, because the uncertainty in position, velocity, energy, and time of observation is substantial to warrant a probabilistic study. Such a study is embodied in a subject commonly referred to as "quantum physics."

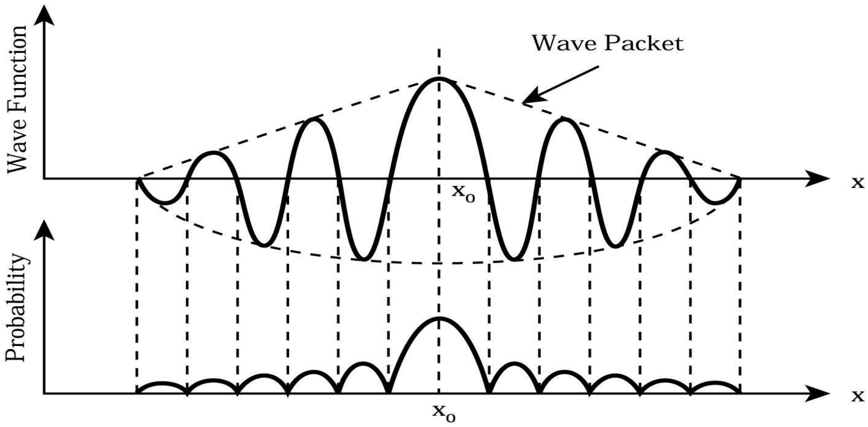
This brings us to one of the most common enigmas in the sciences today: "When is something considered to be a particle and when is it a wave?" To answer such a question, we need to break down the problem into its components.

In the first place, we can observe that a matter particle is a "condensed form of **energy.**" Secondly, a wave is considered to be "**energy** in motion." Thus, by a simple comparison we can see that both have "energy" as their common denominator. In other words, matter and energy are related at the source, since they are cut from the same cloth, figuratively speaking. This means that when a "particle" is in motion, it is actually "energy in motion," therefore naturally, we expect it to behave like a "wave." That expectation is expressed elegantly in the de Broglie's theory.

Upon further examination of the facts, we can observe that:

a) When we are considering a traveling "body" (such as a baseball), which is involved in large spaces, we are dealing with a definite particle. It is a particle with an exact location, because it is behaving on a classical level, which is deterministic and well known.

b) On the other hand, dealing with relatively small spaces that are on the order of atomic or subatomic levels, leads us to quantum physics, where the location of a particle (such as an electron) becomes indeterminate since its existence is uncertain and can only be expressed in terms of a probability. A particle's inexact location is now associated with a "wave packet," and thus, we have to describe it as a wave as shown below.



A Particle's Wave Packet In Terms Of The Wave Function **(Upper),** *And Probability* **(Lower)**.

From the above discussion, we can conclude that to understand the subject of particle-wave theory and answer the question of whether something is, "A particle or a wave," we need to ask a prior question, ***"What is the size of the created space in which the particle is placed?"*** *The answer will solve our dilemma. Thus, it is a question of size of the created space under observation that will provide the resolution to this riddle.*

"No problem can be solved from the same level of consciousness that created it."

—Albert Einstein (1879-1955)
German Born American Physicist, Nobel Prize in 1921

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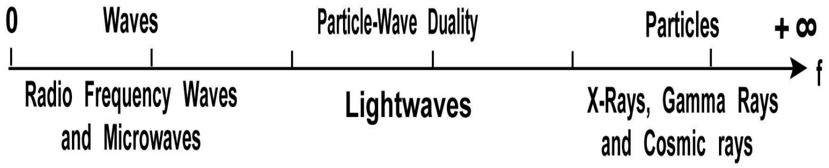
The Dual Theory of Light

Since wavelength (λ) of a wave and its frequency (f) have a reciprocal relationship ($f=c/\lambda$, c being the speed of light), the energy of a photon in electron volts (eV) can be calculated to be $1.24/\lambda(\mu m)$. Thus, we can see that shorter wavelengths have a higher quantized energy and behave more like a particle than a wave as shown below.



The Concept Of Waves And Particles On The Frequency Scale.

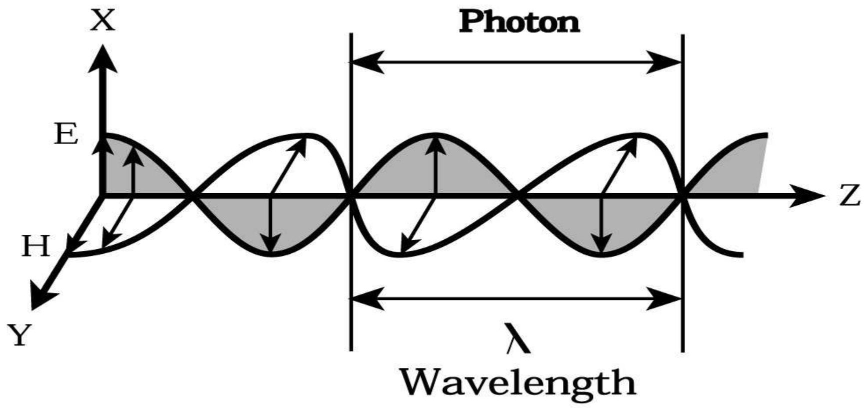
In other words, wave-like effects such as diffraction and interference become more difficult to discern as the wavelength becomes shorter. For example, X-rays and Gamma-rays ($f=3x10^{18}$ Hz) are very high frequency signals and operate at extremely short wavelengths, thus, almost always behave like a collection of particles (i.e., $E=1.24x10^{4}$ eV, a high energy-density particle); whereas radio waves and microwaves ($f=3x10^{10}$ Hz) are much lower in frequency and have much bigger wavelengths and almost always behave like waves (i.e., $E=1.24x10^{-4}$ eV, a low energy-density particle).

The frequency of light in the optical region ($f=3x10^{14}$ Hz) is such that both particle-like and wave-like behaviors occur (i.e., E=1.24 eV), which is a twilight zone of wave-particle existence.

The dual theory of light is based upon the observation and experiments about electron beams, being a stream of particles, which have wavelike properties and behave like light beams. This observation was confirmed by electron diffraction experiments, in which electron beams would diffract when a crystal structure was placed in their path.

The dual theory of light is obtained through years of observation and experimentation with light. It can be concisely stated as:

1) Light demonstrates a wave-like property in which it behaves like an electromagnetic wave as in classical physics. Furthermore, light also has a particle-like property, in which it behaves like a localized particle of matter as in quantum physics as shown below.

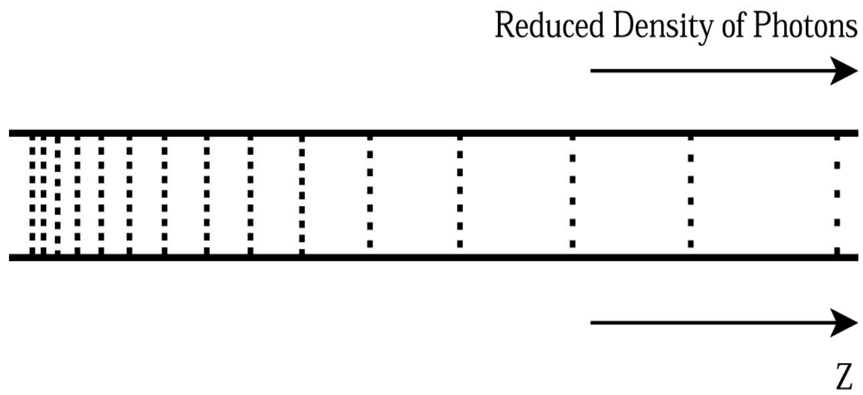


A Photon In A Sinusoidal Wave.

2) A light beam of frequency (f) is composed of a stream of photons, particles possessing energy (E), which is proportional to its frequency multiplied by a constant called the Planck's constant ($h=6.62x10^{-34}$ Js).

3) The intensity of light decreases with increasing distance at any point in space, and is equal to a) The average power per unit area of the waves, or b) The density of the photons at that location is shown on the next page.

There is a strong similarity between light beams and electron beams in that they both travel rectilinearly, reflect and refract at an interface, and diffract in a similar manner.



A Decrease Of Intensity Of Light.

(The closer the dashed lines, the higher the intensity)

Diffraction, in the case of a light wave, occurs due to a varying refractive index (such as a grating), which is analogous to the case of electron beams traveling through a varying force field (such as a crystal lattice). Mathematically speaking, both are analogous and equivalent.

Both of these phenomena can be described using classical wave theory. However, in the optical case, the refractive index changes over dimensions comparable to the light beam's wavelength, while in the case of an electron beam, the force field varies over a distance of the order of a de Broglie's wavelength (defined to be the wavelength of the wave associated with a moving particle of matter). In this case, we need to employ quantum physics (particularly Heisenberg's uncertainty principle) to explain the resulting probabilistic nature of the observed phenomena.

We can see that actual facts are quite contrary to the common belief of "mass of a photon being zero." This points out another pitfall in modern physics education where careless reporting of facts can cause havoc in one's study of the subject.

"In essence, science is a perpetual search for an intelligent and integrated comprehension of the world we live in."

—Cornelius Van Neil (1897-1985)
Dutch Educator and Pioneer of Microbiology