Wave - Particle Duality

of Light

A Brief History of humanity’s understanding of light

“And God said, Let there be light: and there was light.”

~428 BC:Plato and Euclid taught:

“light consists of streamers emitted by the eye.’’

~400 BC:The Pythagorean school:

“Light emanates from luminous bodies to the eye in the form of very fine particles.”

~450 BC:Empedocles:“Light is composed of high-speed waves of some sort.”

1700’s: Isaac Newton:“Light is a stream of particles or corpuscles.’’

1700’s: Christian Huygens:“Light is described by wave theory.”

The controversy continues….

1801: Thomas Young's double-slit experiment seems to prove light to be a wave phenomena.

1862: James Clerk Maxwell shows that light is energy carried in electromagnetic waves.

1887: Heinrich Hertz experimentally verifies the theory of Maxwell.

1905: Albert Einstein demonstrates that light in its interactions with matter must be considered to be tiny packets of energy (photons).

1916: Robert Millikan verifies every aspect of Einstein's postulate.

What is meant by “duality?”

What are (classical) particle properties one can observe?

Particles are considered to be localized packets of energy.

Interactions between particles occur on a local scale.

What are wave-like properties one can observe?

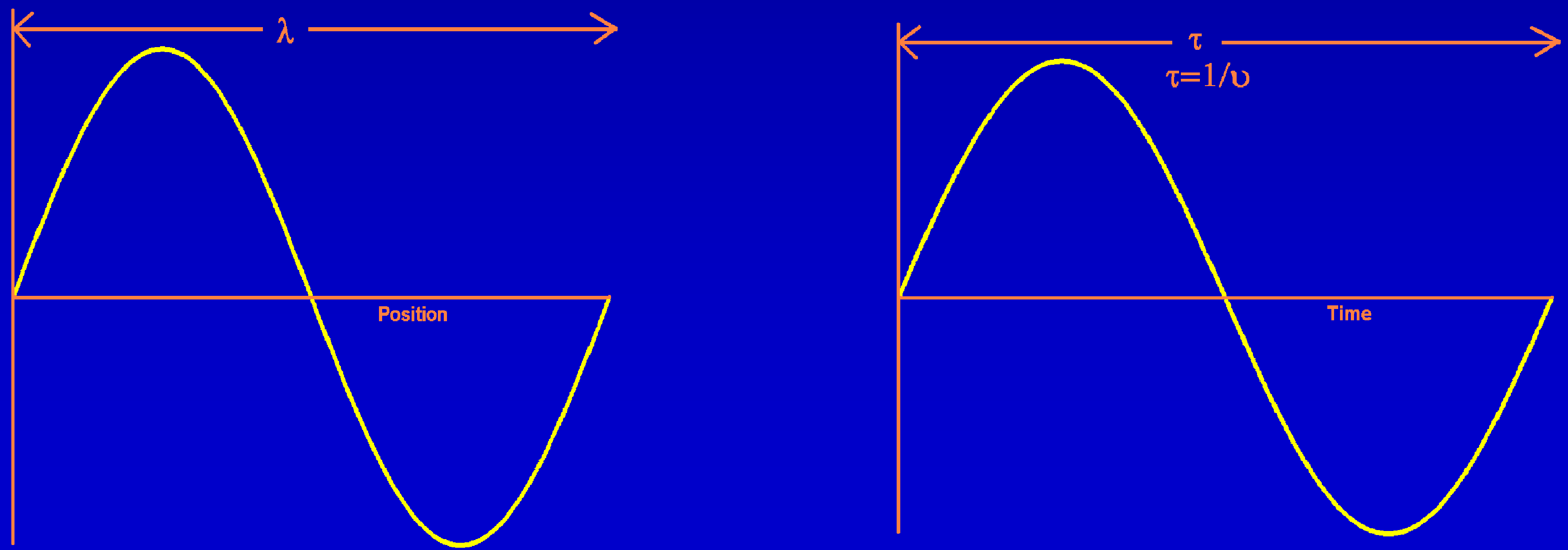
Waves should show interference.

Interactions between waves occur on a disperse scale.

Light as a wave

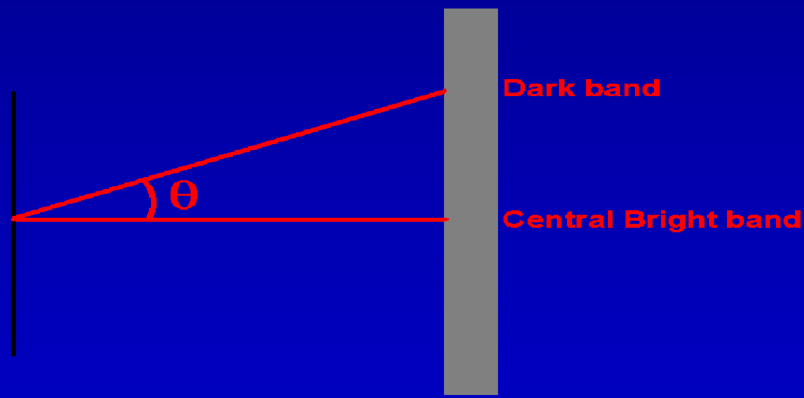
Waves are characterized by a wavelength (λ), a frequency (ν) and also a speed (V).

These quantities are related by $\nu\lambda$=V. Since the speed of light is c, this becomes $\nu\lambda$=c=constant.



If light is a wave, it must show interference. This can provide a simple method for measurement of the wavelength of light.

For single slit diffraction, dark fringes occur when $\sin(\theta)=m(\lambda / w)$, $m=1,2,3,\ldots$

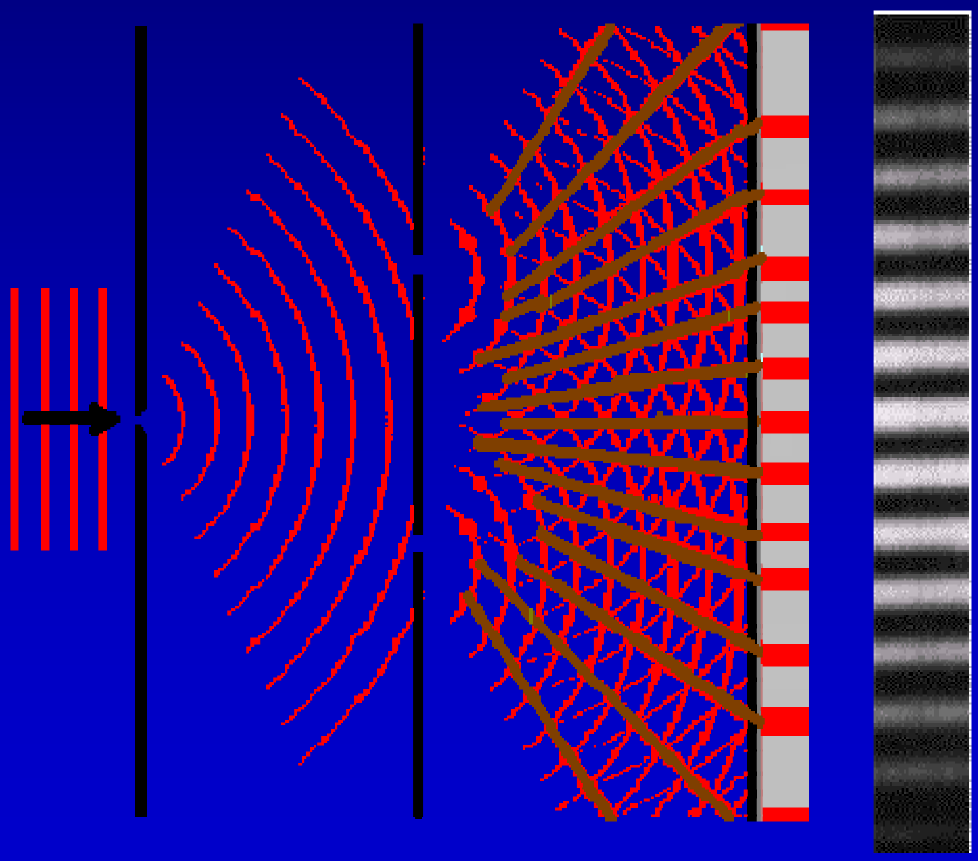


By saying that a band is bright, the physicist measures intensity (I) which is almost energy.

In fact intensity is power per unit area:

I=(Energy / time) / area = Power / area

Young’s Double slit experiment

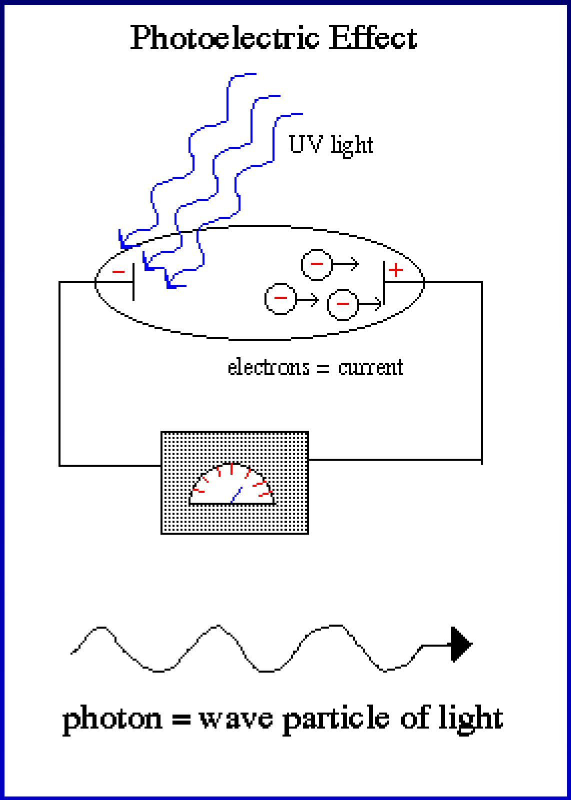


What would happen to the interference pattern if we reduced the intensity to the point that only one photon could be in the system at a time?

In fact, the interference pattern still results! This means that the photon samples the experiment, retains information about origins from a coherent source and that the wave-like properties must necessarily result in an interference pattern.

This is also an example of Bell’s Theorem from quantum mechanics.

The photoelectric effect



Observations:

No time lag between turning on light and ejection of electrons.

Easy to observe with violet or ultraviolet light but not with red light.

Rate of electron emission is proportional to light brightness.

Maximum electron energy depends upon frequency of light, not brightness.

Low speed collisions between Particles

Collisions conserve momentum

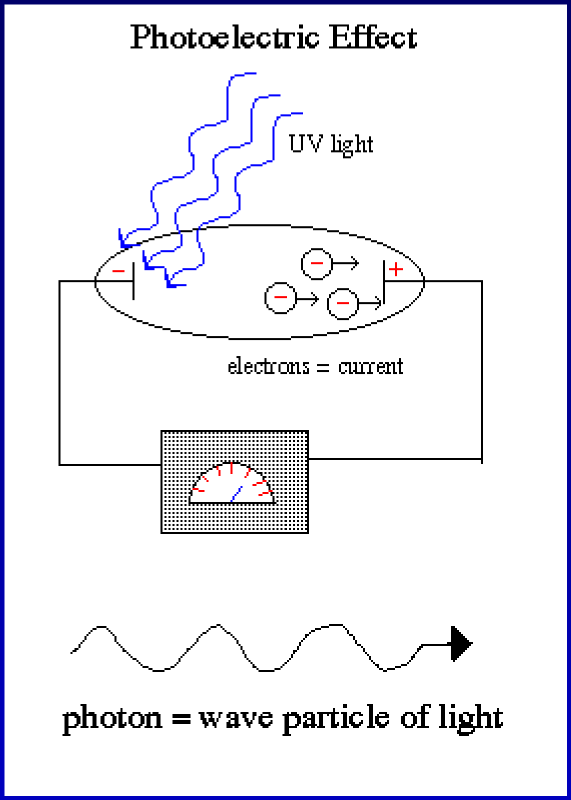
Collisions may also conserve kinetic energy

Mass: $m = \mathbf{F}/\mathbf{a}$

Momentum: $\mathbf{P} = m\mathbf{v}$ (direction and magnitude)

Energy: $E = (1/2)mv^2 = p^2/(2m)$

The photoelectric effect



Observations:

No time lag between turning on light and ejection of electrons.

Easy to observe with violet or ultraviolet light but not with red light.

Rate of electron emission is proportional to light brightness.

Maximum electron energy depends upon frequency of light, not brightness.

Per Einstein: photons are completely absorbed by each electron ejected from the metal. This is an all-or-none process. In addition, the energy of a photon is proportional to frequency of the photon.

Light as a particle

The mass of a photon is zero.

Observation: Photons exert a force on objects they strike. Therefore photons must possess momentum.

We can not then define momentum as $p=mv$.

We can define the momentum of a photon in terms of the energy of a photon. The result is:

$$p=E/c$$

Where c is the speed of light.

This is a consequence of a more general expression for the connection between energy, mass and momentum:

$$E^2=m^2c^4+p^2c^2$$

Light shows both particle and wave properties. Can it be the case that this duality is a more general property of nature?

1924: Louis de Broglie postulates that all matter has a wavelength.

$\lambda = h/p$ where $h = 6.6 \times 10^{-34}$ Joule-s

If matter is both a wave and a particle, what does this imply for measurement of fundamental quantities?

Werner Heisenberg postulates the "Heisenberg uncertainty principle:"

$$\Delta p \Delta x \geq h/2\pi$$

and

$$\Delta E \Delta t \geq h/2\pi$$

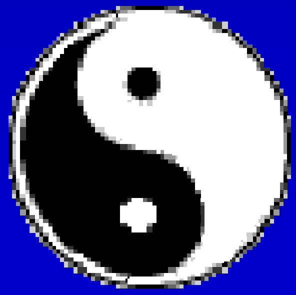
Concept of duality is fundamental!

Niels Bohr formulated an explicit expression of the wholeness inherent in duality.

Quantum phenomena exhibit complementary properties-appearing either as particles or waves-depending on the type of experiment in which they manifest.

To observe particle properties: investigate individual exchanges of energy and momentum.

To observe wavelike properties, examine spatial distribution of energy.



A complete description of quantum phenomena must necessarily include opposites into one entity much as the union of yin and yang forms a whole: with birth, there must be death.