Wave-particle duality

The energy received by a radio antenna comes as a wave, whereas at the same time the same electromagnetic radiation received by a photo-electric material as light particles or photons. There are similar examples of the electron (which is a particle) behaving like both particle and wave. This phenomenon is known as ***wave-particle duality***.

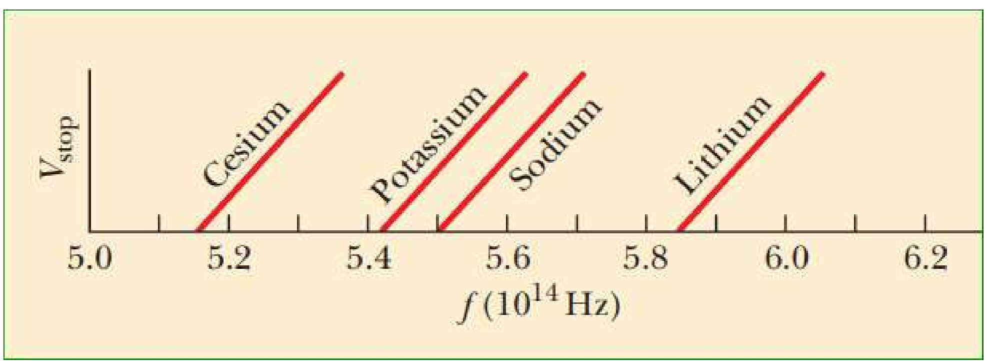
There are some phenomena or experimental results that gave rise to the concept of wave-particle duality. They are the Photoelectric effect, Compton Scattering, and Blackbody radiation.

1. Photoelectric Effect:

When light of high enough frequency falls on a clean metal surface, electrons are emitted from the surface by photon– electron interactions within the metal. The governing relation is

$$hf = K_{max} + \Phi, \qquad (38\text{-}5)$$

in which hf is the photon energy, K_{max} is the kinetic energy of the most energetic emitted electrons, and Φ is the work function of the target material—that is, the minimum energy an electron must have if it is to emerge from the surface of the target. If hf is less than Φ, electrons are not emitted.



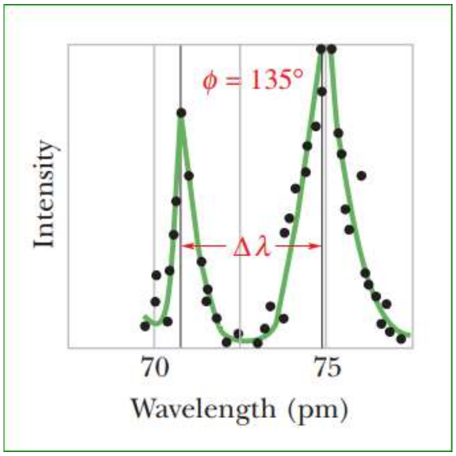
The above figure shows that different work function Φ for four elements are plotted against the frequency of the incident light. (if we multiply frequency with Planck's constant we get the photon energy, E = hf)

2. Compton Shift:

When x rays are scattered by loosely bound electrons in a target, some of the scattered x rays have a longer wavelength than do the incident x rays. This Compton shift (in wavelength) is given by,

$\Delta\lambda = h/mc\,(1 - \cos\varphi)$ (38-11)

in which φ is the angle at which the x rays are scattered. $\Delta\lambda$ is the difference between the wavelengths of the incident and outgoing x rays, h is the Planck's constant, m = mass of an electron, and c = velocity of light.



The figure on the left shows the two peak intensities of the outgoing x-ray during a Compton Scattering experiment.

$\varphi = 135^0$ is the angle at which the x rays are scattered and, $\Delta\lambda = (75 - 70.8)$ pm. $\Delta\lambda = 4.2 \times 10^{-12}$ m. It is the difference between the wavelengths of the incident and outgoing x rays.

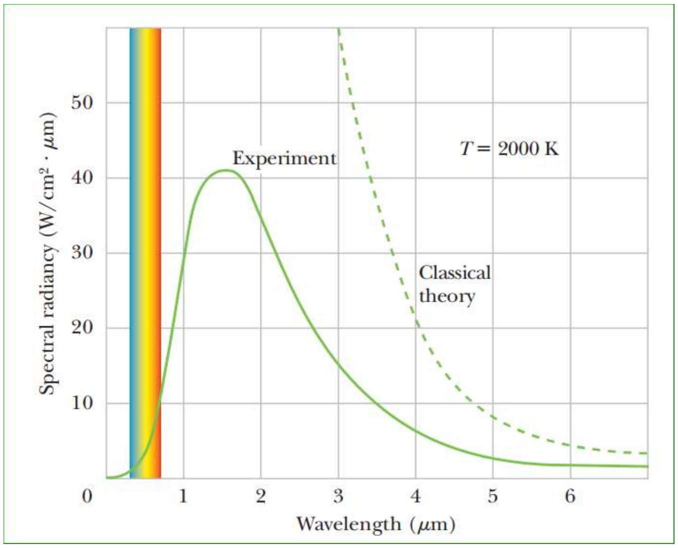
3. Ideal Blackbody Radiation:

As a measure of the emission of thermal radiation by an ideal blackbody radiator, we define the spectral radiancy $S(\lambda)$ in terms of the emitted intensity per unit wavelength at a given wavelength λ. For the Planck radiation law in which atomic oscillators produce the thermal radiation, we have (38-14).

where h is the Planck constant, k is the Boltzmann constant, and T is the temperature of the radiating surface. Wien's law relates the temperature T of a blackbody radiator and the wavelength λ_{max} at which the spectral radiancy is maximum:

$\lambda_{max}T = 2898\ \mu m\ K.$ (38-15)

To explain the experimental results Einstein proposed that light is quantized. It means a light wave consists of an integral multiple of a smaller quantity (or quanta), he termed the light quanta as ***"Photon"***. The experimental result is plotted with a light-green solid line and the dotted line shows the classical explanation of the radiation.



If light is absorbed and emitted as a continuous form, as the classical theory demands, that it can't explain the experimental data.

When Planck used light as composed of streams of individual photons of energy hf, only then he would be able to explain the data.

Photon energy and momentum:

An electromagnetic wave (light) is quantized, and its quanta are called photons. For a light wave of frequency f and wavelength λ, the energy E and momentum magnitude p of a photon are

$E = hf$ (photon energy) (38-2)

and $p = hf/c$

or $p = h/\lambda$ (photon momentum). (38-7)

Light Waves and Photons:

When light interacts with matter, energy and momentum are transferred via photons. When light is in transit, however, we interpret the light wave as a probability wave, in which the probability (per unit time) that a photon can be detected is proportional to, where Em is the amplitude of the oscillating electric field of the light wave at the detector.

Matter Waves:

A moving particle such as an electron or a proton can be described as a matter-wave; its wavelength (called the de Broglie wavelength) is given by λ = h/p, where p is the magnitude of the particle's momentum. *We need to calculate matter waves for electrons and other subatomic particles as an exercise.*

The Wave Function:

A matter-wave is described by its wave function Ψ (x, y, z, t). It means the Ψ is a function of x, y, z that is position and time. For a particle of mass m moving in the x-direction with constant total energy E through a region in which its potential energy is U(x), Ψ(x) can be found by solving the simplified Schrödinger equation:

A matter wave, like a light wave, is a probability wave in the sense that if a particle detector is inserted into the wave, the probability that the detector will register a particle during any specified time interval is proportional to $|\Psi|^2$, a quantity called the probability density.

Heisenberg's Uncertainty Principle:

The probabilistic nature of quantum physics places an important limitation on detecting a particle's position and momentum. That is, it is not possible to measure the position and the momentum of a particle simultaneously with unlimited precision. The uncertainties in the components of these quantities are given by, (38-28)

$\Delta x.\ \Delta p_x \geqq \hbar$

$\Delta y.\ \Delta p_y \geqq \hbar$

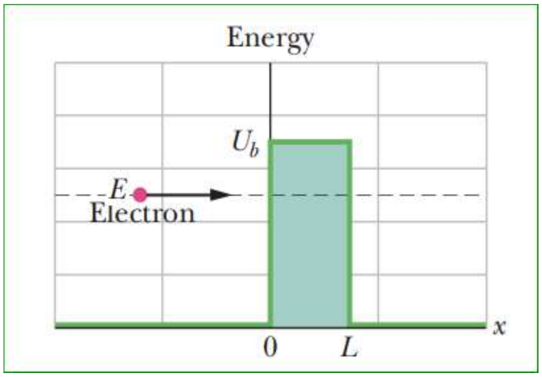
$\Delta z.\ \Delta p_z \geqq \hbar$

Potential Step

This term defines a region where a particle's potential energy increases at the expense of its kinetic energy. According to classical physics, if a particle's initial kinetic energy exceeds the potential energy, it should never be reflected by the region. However, according to quantum physics, there is a reflection coefficient R that gives a finite probability of reflection. The probability of transmission is T 1R.

Barrier Tunneling

According to classical physics, an incident particle will be reflected from a potential energy barrier whose height is greater than the particle's kinetic energy. According to quantum physics, however, the particle has a finite probability of tunneling through such a barrier, appearing on the other side unchanged. The probability that a given particle of mass m and energy E will tunnel through a barrier of height Ub and thickness L is given by the transmission coefficient T.



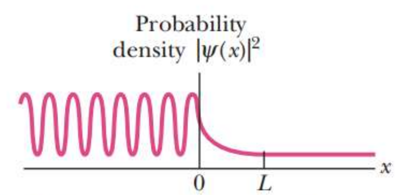


Figure 38-18 A plot of the probability density $|\psi|^2$ of the electron matter wave for the situation of Fig. 38-17. The value of $|\psi|^2$ is nonzero to the right of the potential barrier.

The figure on the left shows an electron encounters a potential barrier of height U_b. Classically it is not possible for the electron to pass it. But if we solve the Schrodinger equation for the electron we find there is some value outside the barrier. Thus we can say that it is possible for the electron to pass through the barrier.

Explaining the strange phenomena of wave-particle duality a new branch of physics has emerged, it is called Quantum Mechanics. It answers such questions as:

Why do the stars shine?
Why do the elements exhibit the order that is so apparent in the periodic table?
How do transistors and other microelectronic devices work?
Why does copper conduct electricity but glass does not?

In fact, scientists and engineers have applied quantum physics in almost every aspect of everyday life, from medical instrumentation to transportation systems to entertainment industries.

Common Questions:

1. Define wave-particle duality. Which experimental results confirm wave-particle duality?
2. What are the photoelectric effect and Compton scattering?
3. What is black body radiation?
4. What is Heisenberg's principle?
5. What is a photon? How did Einstein solve the problem in Black body radiation?