Wave Particle Duality: A Brief Introduction

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1 What Is This Phenomena?

Wave-particle duality is an important concept in the realm of quantum mechanics. In its simplest application, it refers to how light can behave as both a wave and a particle.

For example, maybe you have traditionally seen light as a wave, but in theory, it can behave as a particle too based on how it is observed.

2 The Corpuscle Theory

During the early 18th century, Sir Isaac Newton believed that light was a stream of particles. Newton was a English physicist and mathematician from 1643 to 1727, who would largely be credited for developing the laws of motion. He called these particles of light "corpuscles."

His statement was based on the fact that many abilities of light, such as reflection or even refraction, could be modeled on the subatomic scale as the collective moving of many small particles.

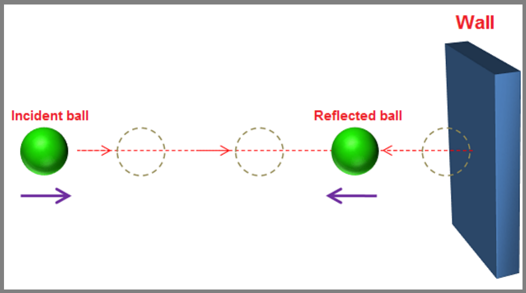

Figure 1: This is how an individual corpuscle would act; now imagine millions of these flowing to create a wave like phenomena

For example, reflection could be seen as individual particles hitting a surface and then bouncing off, such as they were in a collison. Refer to Figure 1 for a visual.

3 Huygens Wave Theory

However, prior to the publication of Newton's "Optiks" (in which he talked about corpuscles), during the late 17th century, Christian Huygens created Huygens' Theory by claiming that light behaved as a wave.

Huygen was a Dutch mathematician from 1629 to 1695 whose theories on light would be revolutionary. While Newton had been able to explain reflection and refraction, he couldn't explain interference through his theory.

Huygen claimed that light behaved as a wave, and had the ability to either interfere constructively or destructively with itself. However, his theory wasn't as widely believed as Newton.

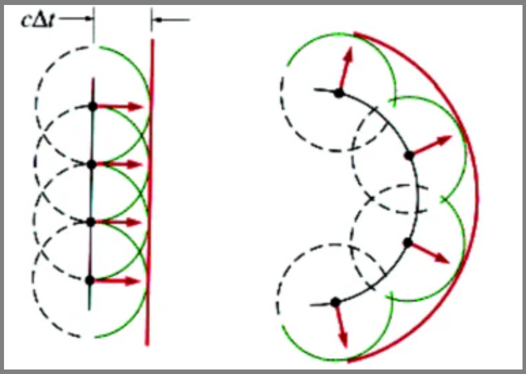

Figure 2: For both images, pretend as if the black line acts as the original wavefront; notice the red arrows, which signify the new wavelets are waves pushing out from the wavefront. The red line represents the new wavefront which these waves produce

More specifically, Huygen believed that wavefront, or the front of a wave, would become a source of new wavelets to create waves; to clearly understand this, think about dropping a pebble into a pond. From the center of where it would hit, circular waves would begin to ripple outwards, creating a new wave front, and repeating the process. Look at Figure 2 for a more specific description.

4 The Original Double Slit Experiment

Eventually, the issue would be addressed by scientist Thomas Young during the 19th century. In the famous double slit experiment, he would send rays of light through two tiny slits onto a black backdrop.

It would clearly be observed that light would pass through the slits and then form interference patterns on the backdrop; that is, the waves would interfere constructively and destructively to create a pattern.

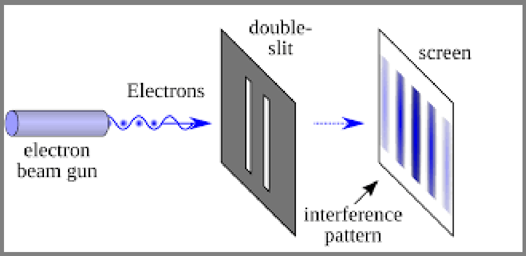

Figure 3: What are interference patterns? Look at the lines formed on the screen; the darker blue lines represent constructive interference due to the waves aligning in such a way that they come together to powerfully showcase light. The lighter fringes represent deconstructive interference, where the waves slightly cancel each other out, reducing the light.

Since it was known that interference patterns are a key property of waves, it was believed that light was a wave. Look at Figure 3 for an accurate set up of the experiment.

5 Experiment Repeated

The experiment would eventually be repeated by Claus Jönsson from Germany. Jönsson would repeat the experiment, but used electrons instead of light.

People believed up until this point that light was a wave and electrons were a particle; but this would change that.

When Jönsson shot the electrons, he would observe a interference pattern being formed on the screen; this implied that the electron was interfering with itself, ultimately showing wave like properties.

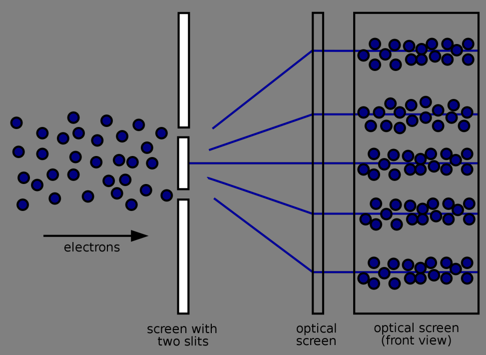

Figure 4: What do waves and particles really mean? When the electrons weren't observed, their position was a probability because we didn't know where exactly they would hit. This is why they acted as waves. But when their specific position was measured, it was evident where they would hit, so they formed discrete dots on the back: particles

However, when each of the electrons were measured as to which slit they went through (as in it was recorded whether the electron passed through slit 1 or slit 2), a interference pattern would not form, but rather individual spots from electron contact

What does this mean? It implied that unless directly observed, electrons demonstrated wave like properties which represented the uncertainty in their position. But if you measured them, they had to become a discrete particle, thus forming discrete dots upon contact on the screen.

6 Energy As Discrete Packets

To understand this, the term "blackbody" should be defined; a blackbody is a object with absorbs and emits radiation perfectly.

It had been believed that the rate at which blackbodies emitted energy should increase to infinity, a process known as ultraviolet catastrophe. However, research would show that this energy emitted was actually a finite amount

To explain this, Max Planck proposed that energy was not continuous, but rather was split into discrete packets, which he would call quanta, or photons. Planck was a German physicist from 1858 to 1947 who would be influential on quantum theory. He created the following equation :

$$\boxed{E = hf}$$

Figure 5: This equation effectively shows how a property of a wave, frequency, can relate to the energy of a particle, reflecting wave light quality.

Here, E represents the energy of a individual photon, h is the famous Planck constant, and f was the frequency of the radiation. For now, just treat h as an arbitrary constant value, as we don't need to understand what it really is.

What does the equation mean? It meant the magnitude of energy in a discrete packet of emission was proportional to the product of the frequency of the emission and Planck constant. Thus, energy was not continuous.

7 Einstein and the Photoelectric Effect

The photoelectric effect is a process where when light shines on a metal, the metal releases electrons. This interpretation views light as a particle, as it is the photons from the light which knock out the loose electrons off of the metal, causing them to be released. Think about it as individual collisions.

For an electron to be able to be knocked out, the photon had to have a energy greater than the work function of the metal; just think of the work function as the smallest amount of energy required to free an electron from the metal.

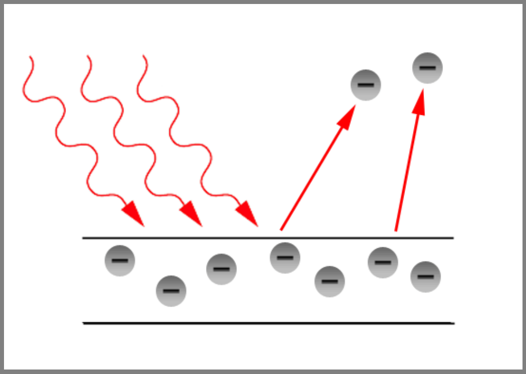

Figure 6: Shows how the beams of light, which can be seen as a continous stream of particles, knock out the electrons from the metal as to cause them to eject; this is basic transfer of energy, since the photons transfer whatever KE is left following overcoming the workfunction to the electrons to be ejected

Einstein would say that an electron would have the energy of $\mathbf{E = hf}$, or Planck Equation. Thus, the frequency was the only thing that mattered in terms of knocking an electron out; you could have infinite intensity, but all this would mean was that more photons were hitting the surface, but they would still have the same energy

To be clear, intensity refers to the number of electrons. The takeaway here is that you could have an infinite amount of electrons, but if none of them have enough energy individually to overcome the workfunction, the photoelectric effect cannot take place.

This reflects wave particle duality, as frequency is a property of light which determined individual energy, but the individual energy of each particle reflects particulate behavior. It shows the interconnection.

8 De Broglie Wavelength

In the early 18th century, Louis de Broglie would show that wave particle duality could apply to all forms of matter. He would do this by creating the De Broglie wavelength. This equation would be modeled as

$$\lambda = \frac{h}{p}$$

Figure 7: Notice that increasing momentum decreases the wavelenth. Keeping in mind that momentum is the product of mass times velocity, that would mean that objects with smaller masses or velocities would have a larger or much more evident wavelength, and vice versa.

Where wavelength is obviously the wavelength, h is again Planck constant, and p is the momentum of the object, it can be seen that any object can be expressed through a wave.

Notice that momentum is at the bottom of the equation, so it is inversely proportional to wavelength. This would mean that objects with greater masses or high velocities would have less of a discernible wavelength (because this would mean a greater momentum). Notice that elementary objects at the subatomic level have very low masses, so they could be expressed as a wave.

This again showed how varying circumstances had the potential of affective a particle based on wave