SASTA OLIPHANT

SCIENCE AWARDS

SOUTH AUSTRALIAN SCIENCE TEACHERS ASSOCIATION

Prize Winner

Science Writing

Year 9-10

Amritha Chulliat

Australian Science and Mathematics School

On the Eccentricities of the Double-Slit Experiment

*"A phenomenon which is impossible, **absolutely** impossible, to explain in any classical way, and which has in it the heart of quantum mechanics."*

- *Richard Feynman, on the double-slit experiment.*

Is light a wave, or a particle?

Before you, stands a question that has undergone investigation for thousands of years.[1] Many notable scientists have proposed their share of ideas, but they conflict with one another, providing no conclusive stance. Before unpacking the question's contents, let's get familiarised with the terms.

Waves are characterised as an energy-carrying disturbance in a medium, sometimes having the trait of periodicity.[2] Particles are elementary, point-like objects that constitute matter and energy.[3]

In his book *Opticks* (1704) Newton advocated for a particle theory of light, arguing that phenomena such as reflection and refraction, featuring light rays propagating in straight lines, were best explained using particles (among other reasons).[1] However, in 1801, a polymath by the name of Thomas Young performed an experiment that contradicted Newton's theory.[4] The general setup of this experiment is seen in Figure 1.

Figure 1. The double-slit experiment.[5]

A monochromatic light source is placed in front of a screen containing two small slits that allow light through, followed by a backstop.[5] Here the light exhibits a curious behaviour, forming an alternating pattern of light and dark bands with the most brightness at the centre. These bands are the result of interference, characteristic of waves. When waves go through an opening of comparable size to their wavelength, they will fan out, or diffract.[6] If both slits produce diffracting waves of light, they overlap while spreading out, interfering with one another, and creating the pattern upon impact with the backstop.

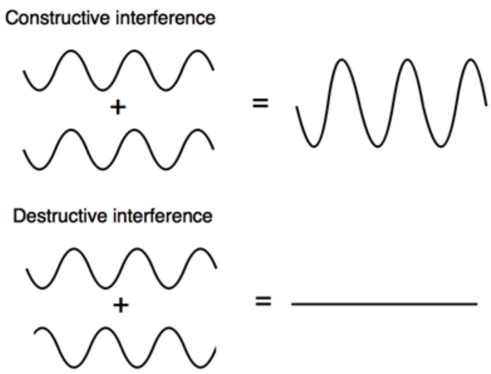

Figure 2. Constructive and destructive interference.[7]

On the Eccentricities of the Double-Slit Experiment

As shown in Figure 2, when the crests of one wave meet the trough of another, their opposite amplitudes add to give a wave with zero amplitude. In the wave model of light, amplitude coincides with brightness, and so the dark bands are areas where the light waves have destructively interfered.[1] When the waves are in phase, they combine to make a wave with a greater amplitude, constructive interference. Consequently, some bands are bright.

The above result is unexpected, because if light is a particle, there must be no interference, and the greatest intensity should be directly opposite the two slits, not in the middle of the backstop.[8] The same experiment with particles of sand reflects these expected observations (Figure 3).

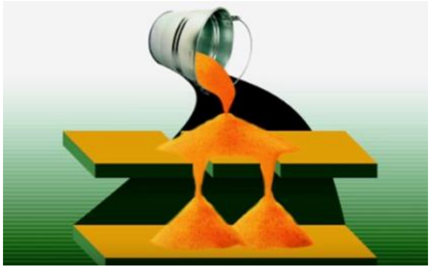

Figure 3. The double slit experiment with sand. The sand peaks directly opposite each slit.[5]

Although this is convincing evidence for light waves, other phenomena, such as the photoelectric effect, still require the particle model of light.[1] Even in the double-slit experiment, the photons (particles of light) arrive as discrete points, and it's the emergent image they create which we call the interference pattern.[9] Sometimes light acts like a particle, sometimes like a wave.

This dual nature is a central concept in quantum mechanics, termed wave-particle duality.[1] Why is light not specified in that term? Because it was eventually realised that this not only applies to light, but also electrons, atoms, and other particles. When the double slit experiment is performed with, say electrons, they too arrive as points and collectively create the interference pattern.

Could the electrons be organising their motion together? To test this theory, we can send the atoms one at a time to see if interference persists. When this adjustment is made, at first, the arrival of the particles seems random, but once enough of them gather, the pattern is back (Figure 4).[5]

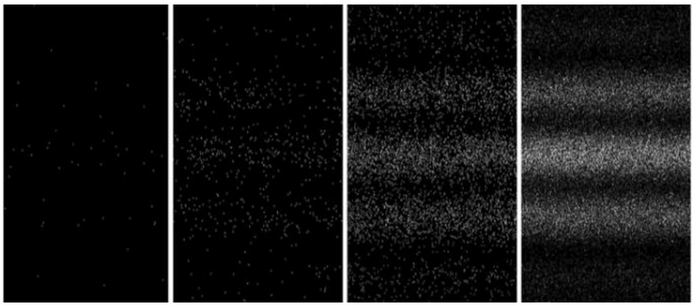

Figure 4. Formation of Interference pattern over time.[10]

Each electron is intrinsically able to land so that it preserves the pattern. Another striking conclusion is that assuming the electron is going through one slit, it should remain unaffected by closing the other, but this is not the case as doing so destroys interference.[11] Then is the electron not going through the slits? No, closing them both destroys interference too, forcing us to conclude this phenomenon requires both slits to be open.

Then what exactly is it doing at the first screen? To find out, we can place a light source between the two slits. Since charges scatter light, when the electron is detected, we will see a flash near the slit it went through, followed by its mark on the backstop.[8] But when this is done, we find the electrons do not create an interference pattern, but rather bands opposite the slits, as seen in Figure 5.

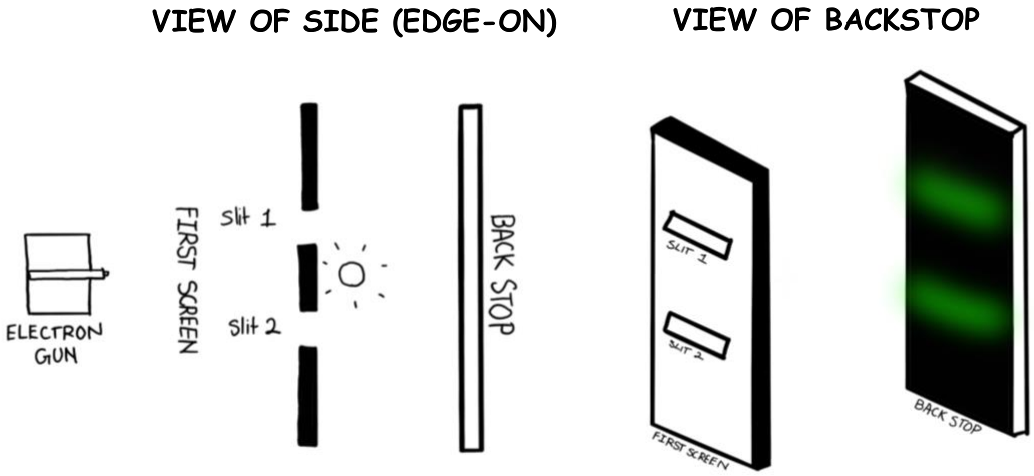

Figure 5. Light source causes electrons to make pattern of two bands (Figure by author).

What has caused this change? The dual nature of light suggests that photons scattering off electrons can jolt them and change their trajectory.[8] Could we minimise this by lowering the brightness? This decreases the rate of photons being emitted, not the individual particle's energy. Still, it does mean that some electrons avoid being seen at the slits and arrive as a dot at the backstop without producing a flash, though the flash is the same intensity as before. However, lowering the brightness reveals another peculiarity. The unseen electrons collect in an interference pattern, while those that scatter light collect in two bands. This is strange; electrons continue to interfere if they don't interact with a photon.

In the early decades of quantum theory, French physicist Louis de Broglie discovered that properties of a particle, like its momentum, had wave-like counterparts, like wavelength.[11] Scientists pondered what it meant for a particle to also be a wave and sought to find a function that could model its shape.[12] The latter was done by Erwin Schrödinger, who developed an equation in 1926 that featured the wave function as a solution.[13]

$$\frac{-\hbar^2}{2m}\frac{\partial^2\Psi}{\partial x^2} + V\Psi = i\hbar\frac{\partial\Psi}{\partial t}$$

Equation 1. The Schrödinger wave equation. The Ψ (psi) symbol represents the wave function.[11]

A conceptual understanding of this function was provided by Max Born, another physicist, who found that the complex square of the wave function for some particle, at some position in space, gave the probability of finding it there.[11] To illustrate this further, imagine an electron inside a 1-dimensional box (Figure 7).

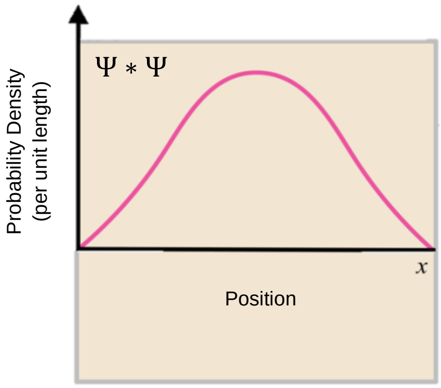

Figure 7. Probability wave of electron inside one-dimensional box. The x-axis represents the box (Figure by author).

One of the strange principles in quantum physics is superposition. According to this principle, the electron in the box, a quantum system, does not have a well-defined position, but its wave function gives an idea of where it is likely to be if interacted with.[14,12] The graph of the wave function's complex square in Figure 7 directly gives this probability, calculated by the area of the curve between any two points, with its total area equalling 1.[15] The wave function can also describe other probabilistic properties, like an electron's radial distance from a nucleus.

Going back to the double-slit experiment, the electrons can now be interpreted as it's wave function. While some waves are impeded by the first screen, others pass through, diffract, and interfere with itself.[14] This requires both slits, supporting our conclusion from earlier. The resultant wave is shown in Figure 8.

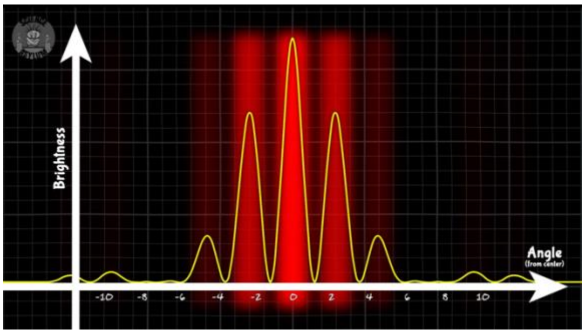

Figure 8. Wave function matched against the interference pattern.[14]

When this wave reaches the backstop, it interacts with it to produce a localised particle.[14] This is called wave function collapse, because the particle's probability is no longer distributed widely, but is concentrated at a location - as shown in Figure 9.

On the Eccentricities of the Double-Slit Experiment

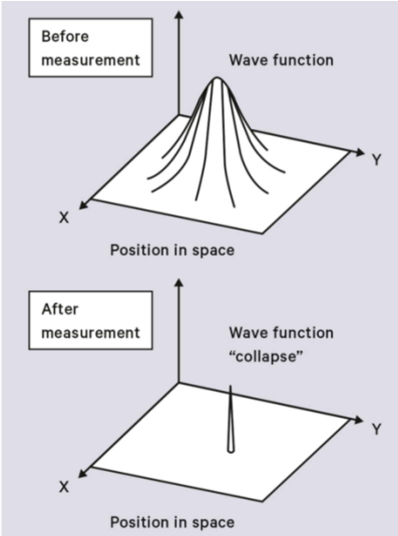

Figure 9. Wave function collapse represented in 3 dimensions.[16]

This probability collapse is seen in coin flips, as when the coin has landed heads, there is no chance that it will land tails. A particle has no chance of appearing 'there' once it has been measured 'here', though there is still the uncertainty principle at play, establishing a basic limitation for the precision with which the quantum's location can be known.[8] This explains the shift in behaviour when a light source is placed at the slits. As the electron wavefunction interacts with a photon, it is forced to localise as a particle prematurely, preventing diffraction or interference.[14] Wave function collapse also occurs during radioactivity and particle collisions.[17]

If we now ask the question of why or how a wavefunction collapses, we tread on speculative turf, as the answer is not clear. This has been labelled the measurement problem of quantum physics. Some suggest the issue is irrelevant, claiming science is about describing phenomena and not understanding it, while others claim collapse is the result of interacting with macroscopic systems.[12] One interpretation in particular rejects collapse and states that all outcomes do occur – in parallel universes.

Another question that may arise is: Why are these effects not observed in our everyday life? While there are more lines of reasoning to explain this, two are described below.

It is a recurring theme in the double-slit experiment that any ability to reveal information about a particle's path erodes quantum effects.[18] A macroscopic object's path information can, in principle, be decoded from its interactions with air and light. The same can be done using its thermal radiation and gravitational influences (mostly large-scale). Secondly, since the de Broglie wavelength of a particle is inversely proportional to its momentum, the relatively big mass, and thus momentum, of macroscopic objects means this wavelength becomes so small as to be negligible.[8] The curve in Figure 8 becomes so high a frequency as not to be a distinguishable wave, the result being no interference behaviour. In short, it's almost impossible to isolate a 'big' object enough to see quantum behaviours.

It should be noted that the reasons above lack the trait of explaining how exactly the macroscopic world emerges from quantum particles but fulfil their job in describing why, for example, a tennis ball does not diffract.

On the Eccentricities of the Double-Slit Experiment

From the above discussion, we see the diversity of questions that this single experiment has offered. The novel behaviour of once familiar physical phenomena has opened the curtains to a stranger and more wonderous universe, one that challenges the intuition of both scientist and layman. Almost all quantum phenomena (wave-particle duality, entanglement etc.) can be seen in different variations of the double-slit experiment, making it a special case of empirical work. But what of the question we asked at the beginning – Is light a particle or a wave? The answer isn't straightforward. It isn't ever both at the same time, nor exclusively one over the other. In fact, it behaves like it is *neither*.

Sounds outrageous? We felt the same way when the sun was discovered to be centre of the solar system, when we first learnt that humans and other life share common ancestors, and when, a little over a century ago, the notions of absolute space and time were revolutionised by a certain Swiss patent clerk.

Nature doesn't submit to our intuition. Quantum mechanics has withstood immense experimentation and produced some of the most accurate predictions in scientific history.[19]

Nevertheless, despite the field's uncertain, probabilistic, and perplexing traits, we can be sure that the double-slit experiment has given us a new set of clues for probing the workings of reality.

Word Count: 1657

On the Eccentricities of the Double-Slit Experiment

Bibliography

1. Physics Explained. What is Wave Particle Duality? [Internet]. YouTube. 2020 [cited 2023 May 30]. Available from: https://www.youtube.com/watch?v=k581_XpaTnU&ab_channel=PhysicsExplained

2. The Editors of Encyclopaedia Britannica. Wave | Behavior, Definition, & Types | Britannica. In: Encyclopædia Britannica [Internet]. 2023 [cited 2023 Jun 17]. Available from: https://www.britannica.com/science/wave-physics

3. Oramous J, Segal S. Particle Definition & Examples | What is a Particle? - Video & Lesson Transcript | Study.com [Internet]. study.com. 2021 [cited 2023 Jun 17]. Available from: https://study.com/academy/lesson/what-is-a-particle-definition-theory-quiz.html

4. The Editors of Encyclopaedia Britannica. Light - Exploring Constructive and Destructive Effects with Young's Double-Slit Experiment | Britannica. In: Encyclopædia Britannica [Internet]. 2023 [cited 2023 Jun 29]. Available from: https://www.britannica.com/science/light/Youngs-double-slit-experiment

5. The Royal Institution. Double Slit Experiment explained! by Jim Al-Khalili [Internet]. YouTube. 2013 [cited 2023 Jun 17]. Available from: https://www.youtube.com/watch?v=A9tKncAdlHQ&t=1s&ab_channel=TheRoyalInstitution

6. Abramowitz M, Davidson MW. Diffraction of Light | What is Diffraction? | Olympus LS [Internet]. Olympus-lifescience.com. 2020 [cited 2023 Jun 17]. Available from: https://www.olympus-lifescience.com/en/microscope-resource/primer/lightandcolor/diffraction/#:~:text=More%20specifically%20when%20applied%20to,smaller%20than%20that%20light's%20wavelength.

7. Physics - Interference [Internet]. University of Birmingham. 2023 [cited 2023 Jun 29]. Available from: https://www.birmingham.ac.uk/teachers/study-resources/stem/Physics/interference.aspx

8. Feynman RP. Chapter 6. Quantum Behaviour. In: Six Easy Pieces. Basic Books; 1994.

9. The Royal Institution. Wave-Particle Duality Explained with Double Slit Experiments - Christmas Lectures with Neil Johnson [Internet]. YouTube. 2019 [cited 2023 Jun 17]. Available from: https://www.youtube.com/watch?v=O81Cilon10M&ab_channel=TheRoyalInstitution

10. Harada K, Akashi T, Niitsu K, Shimada K, Ono YA, Shindo D, et al. Interference experiment with asymmetric double slit by using 1.2-MV field emission transmission electron microscope [Internet]. Vol. 8, Nature. 2018 [cited 2023 Jun 8]. Available from: https://www.nature.com/articles/s41598-018-19380-4

11. Polkinghorne J. Quantum Theory: A Very Short Introduction. OUP Oxford; 2002.

12. Khan Academy. Quantum Wavefunction | Quantum physics | Physics | Khan Academy [Internet]. YouTube. 2018 [cited 2023 Jun 29]. Available from: https://www.youtube.com/watch?v=OFwskHrtYQ4&ab_channel=KhanAcademy

13. Erwin Schrodinger - Facts [Internet]. NobelPrize.org. [cited 2023 Jun 12]. Available from: https://www.nobelprize.org/prizes/physics/1933/schrodinger/facts/#

14. The Science Asylum. How do we KNOW light is a wave? [Internet]. YouTube. 2019 [cited 2023 Jun 17]. Available from: https://www.youtube.com/watch?v=aQ4KzsoCfYg&ab_channel=TheScienceAsylum

15. The Science Asylum. Quantum Wave Functions: What's Actually Waving? [Internet]. YouTube. 2019 [cited 2023 Jun 17]. Available from: https://www.youtube.com/watch?v=vShpwplJyXk&t=388s&ab_channel=TheScienceAsylum

16. Falk D. Parallel worlds – science or sci-fi? [Internet]. Cosmos. 2017 [cited 2023 Jun 29]. Available from: https://cosmosmagazine.com/science/physics/parallel-worlds-science-or-sci-fi/

17. Collapse of the Wave Function [Internet]. Informationphilosopher.com. 2020 [cited 2023 Jun 14]. Available from: https://www.informationphilosopher.com/solutions/experiments/wave-function_collapse/

18. Ash A. Why don't quantum effects occur in large objects? double slit experiment with tennis balls [Internet]. YouTube. 2020 [cited 2023 Jun 18]. Available from: https://www.youtube.com/watch?v=YbrxK1XMmVA&list=WL&index=18&t=697s&ab_channel=ArvinAsh

19. Lewis PJ. Interpretations of Quantum Mechanics [Internet]. Internet Encyclopedia of Philosophy. University of Miami; 2016 [cited 2023 Jun 29]. Available from: https://iep.utm.edu/int-qm/#:~:text=Quantum%20mechanics%20(in%20the%20form,in%20the%20history%20of%20science

.