On the nature of light and its models

Ampolla d'aigua

22nd October 2021

Supervised by [tutor 1],
[tutor 2] and [Programa Argó advisor]
Year 2021-2022

Throughout all our efforts, in every dramatic struggle between old and new views, we recognize eternal longing for understanding, the ever-firm belief in the harmony of our world, continually strengthened by the increasing obstacles to comprehension.

Albert Einstein and Leopold Infeld

I would like to thank the Programa Argó and [Programa Argó advisor] for their help with my project, as well as for allowing me to carry out my experiments in one of the UAB's laboratories. I would also like to acknowledge [grammar corrector 1] and [grammar corrector 2] for their useful comments regarding the grammar and vocabulary of this paper.

Abstract

La llum és un fenomen amb el qual tots estem familiaritzats, però sobre el qual en sabem molt poc. Al llarg dels segles, la recerca sobre la llum ha estat sotmesa a un gran debat en el qual les idees corpusculars s'oposaven a les ondulatòries. Després de molts anys i molta evidència semblava que tots els arguments donaven suport a la teoria ondulatòria, i que, després de tot, la llum era una ona. Malgrat això, a principis del segle XX la predominança ondulatòria se'n va anar en orris quan es va descobrir que la llum estava quantitzada. La comunitat científica d'aleshores estava confosa: per què canviava el comportament de la llum en funció de la situació? El meu treball analitza la naturalesa de la llum per intentar esbrinar quin és el model que millor s'adapta i explica aquest fenomen. Per aconseguir aquest propòsit, començo donant una ullada a totes les teories històriques que intenten explicar la llum. Seguidament, davant de la incertesa a la qual arriba la comunitat científica, realitzo dos dels experiments més importants que donen suport a cada teoria: l'experiment de la doble escletxa i l'efecte fotoelèctric. Un cop comprovo que ambdós models (el corpuscular i l'ondulatori) són vàlids, analitzo diferents teories que pretenen donar una explicació a aquest comportament paradoxal. Les quatre teories que considero em porten a la conclusió que avui dia encara no disposem d'un model prou satisfactori per entendre la complexitat de la llum.

Light is a phenomenon that we are all familiar with, but that we know very little about. Through the years, research on light has been subject to a big debate where corpuscular ideas opposed the undulatory ones. After many years and much evidence it seemed as though all arguments favoured the wave theory, and that, after all, light was a wave. However, at the beginning of the 20th century, wave dominance fell apart when it was discovered that light was quantized. The scientific community at the time was confused: why did light change its behaviour according to the situation? My project analyses the nature of light to try to uncover which model adapts and explains this phenomenon best. For this purpose, I start this project by taking a look at all the historical theories that aim to explain light. Next, considering the uncertainty reached by the scientific community, I carry out two of the most important experiments that support each theory: the double slit experiment and the photoelectric effect. Once I verify that both models (the corpuscular and the undulatory) are valid, I analyse different theories that try to give an explanation to this paradoxical behaviour. The four theories I consider finally bring me to the conclusion that to this day there is still no satisfactory enough model to understand light's intricacy.

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1. Introduction

I vividly recall the first time I learned about light in primary school. It was science class and the teacher taught us all about some of its properties, such as reflection, refraction and colours. My ten-year-old self thought that what we were learning was quite logical and intuitive: when I looked in the mirror, I could see my reflection; when I placed a colour pencil in a glass of water, it appeared as though it had bent; after a thunderstorm, the rainbow appeared… Although some properties were more difficult to imagine than others, overall I saw light as a pretty self-consistent and logical phenomenon.

However, as I grew older and science class became more complicated, I realized that light might not be as easy a topic as it seemed at first. In secondary school, I became more interested in science and I enjoyed learning new things online. After watching and reading many videos and articles on physics, I eventually stumbled upon the concept of "the nature of light" and "wave-particle duality". Despite being extremely confused at first because of my poor understanding of the subject, I was fascinated by this strange idea. I realized that as a child I had learned about the basic properties of light, but that I had never questioned what light itself really was.

Given that this year we must complete a research project on the topic of our choice, it came to me naturally to do it on light. More specifically, the nature underlying this not-so-easy concept. There are multiple models and interpretations for light, but they are normally met with scepticism and uncertainty. Therefore, I asked myself the following question: based on the known theories of light, which model best describes its nature and behaviour? In order to tackle this problem, I have set myself a few boundaries so as to solely consider the most discussed and studied models. The four possibilities that will be explored in this project are:

1. The particle model. Light as a particle.
2. The wave model. Light as a wave.
3. The wave-particle duality model. Light as both a wave and a particle.
4. Another model. Light as neither a wave nor a particle.

Based on these ideas and my current understanding of the subject, I have formulated a hypothesis on what the best model of light might be. This hypothesis considers light as a simultaneous expression of both wave and particle-like behaviours. In other words, two models can be attributed to the nature of light (the wave and the particle model), and thus must coexist within this phenomenon. Light must follow some kind of wave-particle duality.

To properly answer my question, I have structured my project in such a way that a variety of ideas are considered and debated.

Firstly, I will look into all the historical ideas and experiments that have been carried out for this purpose. This will not only allow me to better understand how light behaves, but also to get a sense of the different opinions and arguments expressed over the centuries.

Secondly, I will carry out two experiments that support the two main theories, namely the double slit experiment for waves and the photoelectric effect for particles. Experimentation will allow me to corroborate or disprove these two models and help build my own ideas based on observations.

Lastly, I will discuss the most accepted modern theory (that is, wave-particle duality) as well as some quantum-mechanical concepts that help understand it. All the modern ideas will allow me to look at the problem and my previous experimentation from another point of view. Additionally, I will talk about three other alternative models to make sure every theory and idea is considered before a verdict is reached.

In the conclusions, I will attempt to provide a logical and fact-based answer to my question that not only takes into account all the different theories and opinions, but also highlight my own experience from the two experiments.

By following these guidelines, I also set myself three objectives:

1. The first is to understand the different ideas and points of view regarding light and its nature.
2. The second is to justify these theories, either by mathematical or experimental means.
3. The third is to provide a physically coherent idea on light based on the different models.

2. The debate over the nature of light

The question regarding the nature of light has puzzled scientists since the dawn of time, and has consequently become a major source of debate. For centuries, scientists have come up with different theories defending light as either a particle or a wave, but they have not been able to reach a consensus on the question. In this section, I will cover different experiments and theories that aim to give an explanation to this complex phenomenon.

2.1 Early theories

Some of the first evidence on the study of light dates back to Ancient Greece, when Greek philosophers tried to explain the world around them. Properties such as reflection, refraction and colours were precisely studied and understood by the thinkers Ptolemy (100-170 AD), Plutarch (46-119 AD) and Euclid (4th century-3rd century BC). Even the apparent bending of half submerged objects (a direct consequence of refraction) is discussed in Plato's *Republic*.

The propagation of light is another aspect that greatly fascinated them: Euclid thought light travelled in a straight line, and Hero of Alexandria (10-70 AD) stated that light takes the shortest path in between two points when reflected by a mirror. Furthermore, even before, philosophers such as Empedocles (494-434 BC) and Euclid had considered the idea that light and vision were two sides of the same coin, and therefore that light was tightly bound up with the sense of sight and could not exist independently. However, this idea was later proven to be wrong by the Arabian scientist Ibn al-Haytham (965-1040), who explained that light originates from outside sources other than the eye through phenomena such as the camera obscura. Al-Haytham was a remarkable figure in the field of optics, having touched on topics such as the speed of light, refraction and the effects of light in spherical and parabolic mirrors. He was a firm believer in the corpuscular theory, as he believed that light is composed of a continuous stream of small particles travelling in straight lines through space.

Overall, Greek classical ideas on light can be summarized by this statement that Lucretius (99-55 BC) wrote in the 1st century BC:

> First of all very often we may see that light things made of tiny bodies are swift. In this class there is the light of the sun and his heat, because they are made of tiny first-particles, which, as it were, are

> knocked forward, and do not pause in passing on through the space of air between, smitten by the blow from those that follow (Lucretius, 1st century BC: p. 149).

The conclusion reached by Lucretius is understandable taking into consideration the prevalence of atomism during the classical period, a theory proposed by philosophers Leucippus (460-4th century BC) and Democritus (460-370 BC). The classical idea that light is composed of particles would later lay the foundations for the work of 17th century scientists, such as Pierre Gassendi (1592-1655) and Isaac Newton (1643-1727). Despite this, new observations made in the same century allowed for an alternative view on light to be born: the wave theory.

2.2 Particles versus waves

The debate over the nature of light started to take shape during the 17th century, when the corpuscular ideas opposed the newly established wave-like concept of light.

The wave theory broke ground through the works of René Descartes (1596-1650), who in 1637 published *La Dioptrique*, a theory on the nature of light and refraction. To him, light was no more than a movement or pressure originating from a luminous object and transmitting through an aerial medium to the eye. To understand of this idea, Descartes suggests a walking stick analogy: to a blind man, the movement or pressure he feels through the stick helps him identify the body he encounters. Similarly, the transparent medium can be understood as the walking stick, so that when it comes into contact with the luminous body, a movement or pressure is transmitted almost instantly to the other end of the stick, which in this case is the eye. He therefore sensed that there must be a mechanical medium made up of air particles, through which this luminous pressure is able to expand in a vector-like manner in all directions.

Despite this clever idea, during the 1660s French priest Pierre Gassendi published a philosophical treatise in which he defended an alternative thesis. From his view, matter and natural phenomena are composed of atoms that move freely through the void (i.e. empty space), which clearly opposes Descartes' idea of the luminous body and the aerial medium. However, he goes further to say that the information we receive through our senses can be explained in terms of matter, which means that what we use to see, light, has an atomic form.

This idea that light is made of tiny corpuscles was preferred by Isaac Newton, who in 1704 published his ideas in his book *Opticks*. Newton was a firm believer that light travelled in straight lines, because he could observe that light casts a definite shadow after passing through an opening. This led to him creating a model where light is seen as a ray that represents the trajectories of tiny elastic corpuscles.

His theory could successfully explain the phenomenon of reflection, but was unable to provide a satisfactory explanation for refraction. It is easy to picture how a particle is able to bounce in such a way that the angle of incidence coincides with the angle of reflection, but it is rather complex to explain the change in direction of a light ray upon entering a medium of different density. To be able to explain refraction, Newton needed to assume that light corpuscles are attracted to the denser medium and thus are accelerated in the direction of the normal. This would explain the change in direction, but it also meant that light travels faster in a denser medium, which is incorrect.

Nonetheless, he stood by his theory and refused any attempt at explaining light in a wave-like manner, because to him, it was undeniable that light travelled in straight lines:[1]

> The Waves on the Surface of stagnating Water, passing by the sides of a broad Obstacle which stops part of them, bend afterwards and dilate themselves gradually into the quiet Water behind the Obstacle. The Waves, Pulses or Vibrations of the Air, wherein Sounds consist, bend manifestly, though not so much as the Waves of Water. For a Bell or a Cannon may be heard beyond a Hill which intercepts the sight of the sounding Body, and Sounds are propagated as readily through crooked Pipes as through streight ones. But Light is never known to follow crooked Passages nor to bend into the Shadow. For the fix'd Stars by the Interposition of any of the Planets cease to be seen. And so do the Parts of the Sun by the Interposition of the Moon, *Mercury* or *Venus* (Newton, 1730: pp. 362-363).

Newton's light theory was greatly opposed by English scientist Robert Hooke (1635-1703), who was a defendant of the wave theory and expressed similar ideas to those of Descartes. Hooke's theory considered that light is a motion or a pulse transmitted through a medium, a conclusion he reached after having studied other types of waves in his previous work *Micrographia*. In general, Hooke's ideas on light can be summarized with the statement he wrote in his critique of Newton's theory:

[1] The mistake in Newton's ideas lies in the fact that light does diffract. However, for apertures and obstacles that are big enough, the effects of diffraction are negligible and light can be treated as a ray with a straight trajectory.

> If my supposition be granted, that light is nothing but a simple and uniform motion, or pulse of a homogeneous and adopted (that is a transparent) medium, propagated from the luminous body in orbem, to all imaginable distances in a moment of time, and that that motion is first begun by some other kind of motion in the luminous body; such as by the dissolution of sulphureous bodies by the air, or by the working of the air, or the several component parts one upon another, in rotten wood, or putrifying fish, or by an external stroke, as in diamond, sugar, the sea-water, or two flints or crystal rubbed together (Hooke, 1672: p. 14);

This critique of Newton's ideas provides an idea of the will to resolve the question of the nature of light, which was a highly debatable subject at the time. The desire to reach a solution was evident, as seen by the very ending of the critique written by Hooke:

> If Mr. NEWTON hath any argument, that he supposes as absolute demonstration of his theory, I should be very glad to be convinced by it, the phænomena of light and colours being, in my opinion, as well worthy of contemplation, as anything else in the world (Hooke, 1672: pp. 14-15).

Despite this, the debate was far from being settled, as new ideas supporting the wave theory started being developed. One of the most important wave theories was Christiaan Huygens' (1629-1695) ideas on the nature and propagation of light. In 1690, he published his *Traité de la Lumière*, where he gave a solid explanation for the phenomenon of light, as well as for reflection and refraction. Huygens mathematically proved how light consisted of a series of waves propagating through a medium called the luminiferous aether, which he believed to be similar to the spreading of sound waves through air:

> We know that by means of the air, which is an invisible and impalpable body, Sound spreads around the spot where it has been produced, by a movement which is passed on successively from one part of the air to another; and that the spreading of this movement, taking place equally rapidly on all sides, ought to form spherical surfaces ever enlarging and which strike our ears. Now there is no doubt at all that light also comes from the luminous body to our eyes by some movement impressed on the matter which is between the two; since, as we have already seen, it cannot be by the transport of a body which passes from one to the other. If, in addition, light takes time for its passage—which we are now going to examine—it will follow that this movement, impressed on the intervening matter, is successive; and consequently it spreads, as Sound does, by spherical surfaces and waves: for I call them waves from their resemblance to those which are seen to be formed in water when a stone is thrown into it, and which present a successive spreading as circles, though these arise from another cause, and are only in a flat surface (Huygens, 1690: p. 4).

This new model of light allowed Huygens to satisfactorily explain reflection and refraction, even by correctly assuming that light travels slower in a denser medium. Furthermore, in contrast to older theories, he explained the wave-like propagation, reflection and refraction by means of a geometric construction known as Huygens' principle: "Each point on a primary wavefront serves as the source of spherical secondary wavelets[2] that advance at the wave speed for the propagating medium. The primary wavefront at some later time is the envelope of these wavelets" (Tipler and Mosca, 2008: p. 1059).

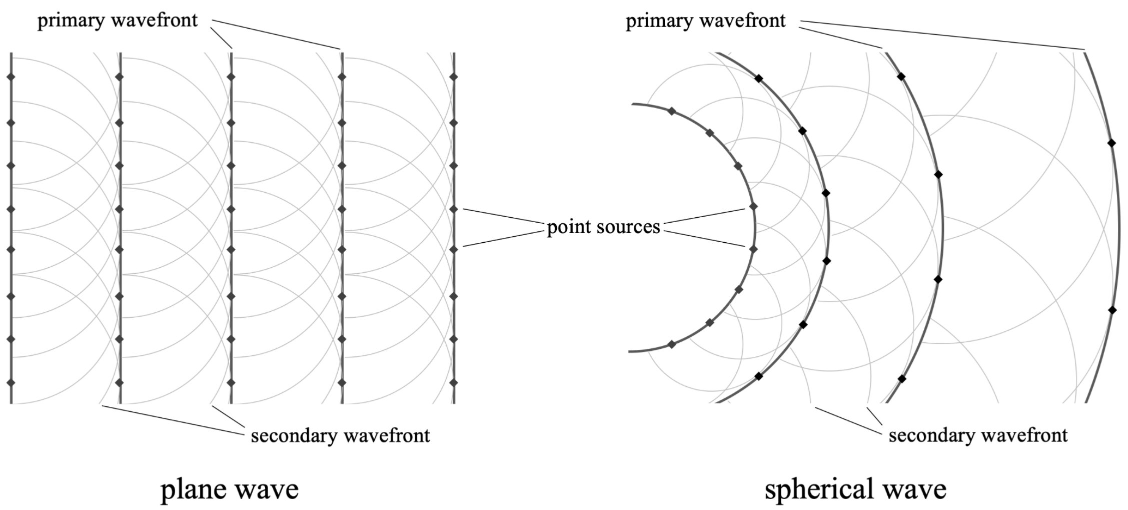

Figure 1 Huygens' principle applied to the propagation of a plane and a spherical wave. Own work.

With Huygens' theory it was made clear that light exhibited a behaviour akin to that of waves, and the more ideas were published favouring the wave theory, the harder it was for those who defended the corpuscular theory to defend themselves. Despite this, Newton's high authority at the time made his opinion on the subject to be considered as more relevant. It was not until new claims in favour of the wave theory were made one hundred years later that the corpuscular theory started to crumble. The inability of Newton's theory to explain the phenomena of diffraction, interference and polarization favoured the prevalence of wave theory during the 19th century.

[2] It is important to note that the fact that each point source creates a spherical secondary wavelet means that a wave is also created in the backward direction, but for simplification purposes, these are often ignored.

2.3 The settlement of the wave theory

At the beginning of the 1800s, British scientist Thomas Young (1773-1829) published a series of articles where he defended and demonstrated the wave-like behaviour of light. Through a series of experiments he was able to observe the diffraction and interference of light, and later published his ideas in an article entitled *On the Theory of Light and Colours*:

> Since every particle of the medium is affected by each undulation, wherever the directions coincide, the undulations can proceed no otherwise than by uniting their motions, so that the joint motion may be the sum or difference of the separate motions, accordingly as similar or dissimilar parts of the undulations are coincident (Young, 1802: p. 34).

From here, he went on to refute Newton's ideas and claim that diffraction is a consequence of light itself:

> It is clearly granted by Newton, that there are undulations,[3] yet he denies that they constitute light; but it is shown in the three first Corollaries of the last Proposition, that all cases of the increase or diminution of light are referable to an increase or diminution of such undulations, and that all the affections to which the undulations would be liable, are distinctly visible in the phenomena of light; it may therefore be very logically inferred, that the undulations are light (Young, 1802: pp. 44-45).

In order to reach these conclusions, Young performed his famous double slit experiment in 1803. The original set-up, however, greatly differs from the modern commonly-known version, and is as follows. First, a tiny hole is made in a window shutter to allow a beam of light to enter the room. Then, a mirror is used to redirect the beam of light in a horizontal direction. Finally, a thin card is placed edgewise in such a manner that the beam is split in half (the diameter of the beam being necessarily greater than the thickness of the card). The result of such a procedure is the display of a pattern of light and dark fringes, which Young attributed to the constructive and destructive interference of light waves diffracting through space.

The modern version was described by Young himself, and it involves the use of a double slit to obtain the same interference pattern. A beam of light is again placed in between an

[3] Newton denied the wave nature of light, but in order to give a proper explanation to the phenomenon of diffraction observed in particular cases, he needed to assume that light corpuscles create a wave in the aether upon interaction with an obstacle.

obstacle, which in this case is two closely spaced slits, and a wave-like pattern is obtained on a screen. One way or the other, this experiment provides undeniable proof that light exhibits a wave-like behaviour upon interacting with tiny obstacles.

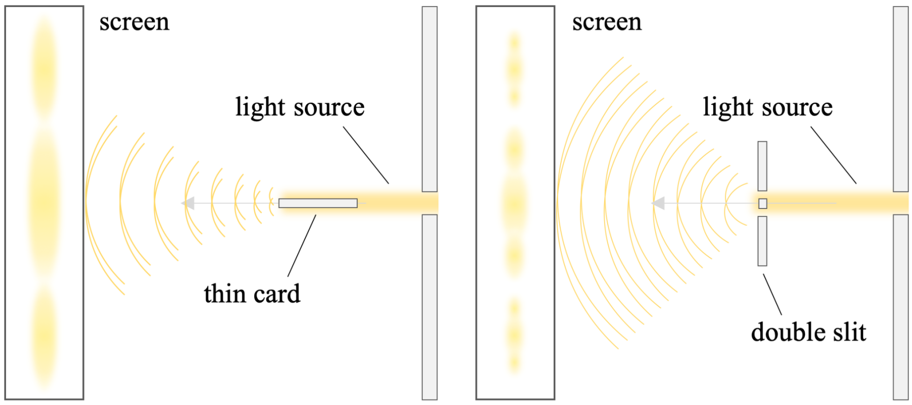

Figure 2 Young's original experiment (left) and the double slit version (right). Own work.

On top of this, Young went on further to prove that even the observations made by Isaac Newton[4] could be explained using the wave theory, as said in his *On the Theory of Light and Colours*:

> As the subject of this proposition has always been esteemed the most difficult part of the undulatory system, it will be proper to examine here the objections which Newton has grounded upon it. [...] As to the analogy with other fluids, the most natural inference from it is this: " The waves of the air, wherein sounds consist bend manifestly, though not so much as the waves of water;" water being an inelastic, and air a moderately elastic medium; but ether being most highly elastic, its waves bend very far less than those of the air, and therefore almost imperceptibly. Sounds are propagated through crooked passages, because their sides are capable of reflecting sound, just as light would be propagated through a bent tube, if perfectly polished within. The light of a star is by far too weak to produce, by its faint divergence, any visible illumination of the margin of a planet eclipsing it; and the interception of the sun's light by the moon, is as foreign to the question, as the statement of inflection is inaccurate (Young, 1802: pp. 27-29).

Finally, to settle his theory once and for all, Young explained how the different colours are related to different wavelengths. He later proved it by calculating the actual values using Newton's experimental data.

[4] See Newton's quote on light and waves (page 10).

Despite Thomas Young's remarkable findings, his ideas were met with a lot of scepticism, as it was first hard to grasp that two rays of light could possibly add up to produce no light. Nonetheless, the appearance of bright and dark fringes is proof that light does not behave in a corpuscular way, as if it did, two bright lines (representing the two slits or the split beam) would be seen on the screen, rather than an interference pattern.

The nature of light became such a problem that concurrently, in 1819, the French Académie des Sciences hosted a contest to be able to definitely settle the question of the diffraction of light. In particular, they were looking for an explanation for the light and dark fringes produced in the zone of transition between the shadow of an object and an illuminated area. The jury of the contest was comprised by scientists François Arago (1786-1853), Siméon Poisson (1781-1840), Jean-Baptiste Biot (1774-1862), Pierre-Simon Laplace (1749-1827) and Joseph Louis Gay-Lussac (1778-1850). All supporters of Newton's theory, they expected a verification of the hypothesized corpuscular explanation, which states that the fringes are produced by a force emanating from the object that causes the shadow (and consequently, the diffraction). The fringes observed could only be explained if this force acted in such a way that attractions and repulsions are continuously alternated.

Only two entries to the contest were received, one of which was by Augustin Fresnel (1788-1827), an engineer and physicist whose ideas were based on Huygens' and Young's. His theory, titled *Mémoire sur la diffraction de la lumière*, follows an explanation on the inaccuracy of the corpuscular theory, and poses an alternative wave-like explanation for the phenomenon. In Fresnel's own words, the fringes can be explained through interferences, a characteristic linked with the wave-like behaviour of light:

> It is thus evident that the hypothesis of contraction and expansion produced by the action of the body upon rays of light is insufficient to explain the phenomena of diffraction. Introducing the principle of interference, however, we are able to predict not only the variation in size of the exterior fringes when the screen is made to approach or recede from the luminous point, but also the curved path of the bright and dark bands. The law of interference, or the mutual influence of rays of light, is an immediate consequence of the wave-theory; not only so, but it is proved or confirmed by so many different experiments that it is really one of the best-established principles of optics (Fresnel, 1819: p. 87).

As has been said before, the judges were firm believers in the corpuscular theory, so they focused on trying to discredit Fresnel's theory. Poisson in particular, thoroughly studied his theory and pointed out an apparent flaw: Fresnel's model predicts that if an opaque disk is irradiated with light, as a consequence of diffraction, a bright spot will appear in the centre of the disk's shadow as if no obstacle were present. To Poisson this prediction was completely absurd, but nonetheless, for scientific accuracy, Arago demanded the experiment be conducted. To everyone's amazement, the result of the experiment was, indeed, that a spot of light can be observed[5] when an opaque disk casts a shadow on the wall.

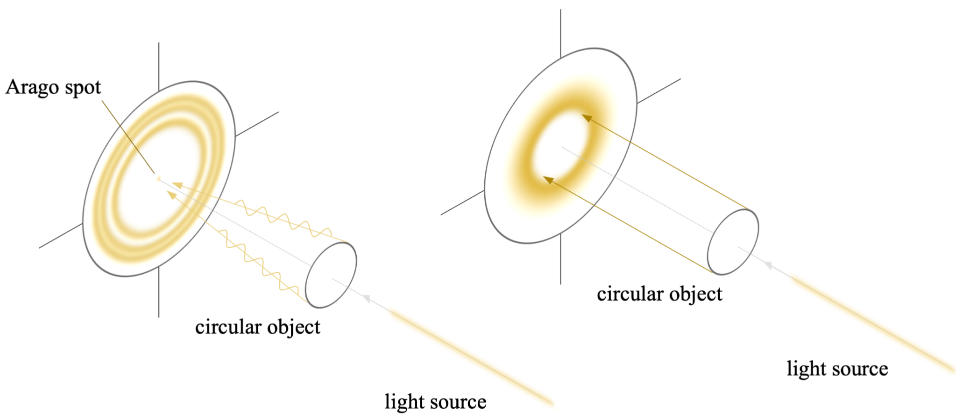

Figure 3 Poisson's experiment if light was a wave (left) and if light was a particle (right). The correct model is the left one (observation of the Arago spot). Own work.

If light had behaved in a corpuscular fashion, no bright spot would have been observed, therefore it was clear that light must be a wave. Fresnel was proclaimed the winner of the contest for his explanation of diffraction, and in the process convinced many corpuscular defendants of the wave-like nature of the phenomenon of light. After the competition, Fresnel went on to study light waves in more detail, so he undertook the polarization of light with Arago. After treating the problem experimentally and mathematically, they concluded light is made up of transverse waves rather than longitudinal waves, as was thought at that time.

The last notable contribution to the classical understanding of light was made by scientists Michael Faraday (1791-1867) and James Clerk Maxwell (1831-1879). It all began in 1845, when Faraday discovered the rotation polarized light undergoes in the presence of a magnetic field (an effect later known as Faraday rotation). This event caused him to look deeper into the subject, and a year later he presented his ideas to the Royal Institution:

[5] In honour of this finding, in optics this spot is often called Arago spot, Poisson spot or Fresnel spot.

> The view which I am so bold as to put forth considers, therefore, radiation as a high species of vibration in the lines of force which are known to connect particles and also masses of matter together. It endeavours to dismiss the æther, but not the vibrations. The kind of vibration which, I believe, can alone account for the wonderful, varied, and beautiful phænomena of polarization, is not the same as that which occurs on the surface of disturbed water, or the waves of sound in gases or liquids, for the vibrations in these cases are direct, or to and from the center of action, whereas the former are lateral. It seems to me, that the resultant of two or more lines of force is in an apt condition for that action which may be considered as equivalent to a lateral vibration; whereas a uniform medium, like the æther, does not appear apt, or more apt than air or water (Faraday, 1846: p. 451).

However, Faraday himself stated in the same explanation that these claims are nothing but hypothetical, and that they needed a lot more consideration before being considered true. He did not necessarily have the mathematical skills to develop further his ideas, and that is where Maxwell came into play. The Scottish scientist read Faraday's contribution and decided to develop it further by investigating electromagnetic fields and light. His most notable work, the Maxwell equations, were accompanied by an attempt to measure the speed of propagation of electromagnetic waves. From his equations he was able to derive a simple expression for the waves' speed in a vacuum, which in modern terms can be expressed as

$$\upsilon = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

Where υ is the velocity of propagation and ε_0 and μ_0 are constants: the former is the value of vacuum permittivity (approximately $\varepsilon_0 \approx 8.85 \times 10^{-12} C^2 \cdot s^2 \cdot kg^{-1} \cdot m^{-3}$), and the latter is the value of vacuum permeability (approximately $\mu_0 \approx 4\pi \times 10^{-7} m \cdot kg \cdot C^{-2}$).

After doing this operation, he obtained a value of approximately $\upsilon \approx 3 \times 10^8 m \cdot s^{-1}$. Maxwell could not help but notice the odd similarity of this result to the predicted values for the speed of light. He therefore concluded that light itself must be some type of electromagnetic wave in his 1861 paper *On Physical Lines of Force*. Four years later, he again published his ideas in *A Dynamical Theory of the Electromagnetic Field*, where he wrote:

> The agreement of the results seems to show that light and magnetism are affections of the same substance, and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws. [...] Hence electromagnetic science leads to exactly the same conclusions as

> optical science with respect to the direction of the disturbances which can be propagated through the field; both affirm the propagation of transverse vibrations, and both give the same velocity of propagation (Maxwell, 1865: pp. 499-501).

Not only was Faraday right about light being an electromagnetic wave, but he also correctly hypothesized that it is a type of transverse wave, just like Fresnel had shown a few years earlier. It was then settled that light must be an electromagnetic wave travelling at a constant speed. Despite this, there was a noticeable disagreement between Faraday's and Maxwell's ideas: Maxwell believed light waves propagated through the known aether, while Faraday dared to dismiss this idea and thought they travelled through a field.

All subsequent theories on the subject of light defended the wave theory, although the medium of propagation had yet to be fully established. The experiment to end this discussion was the Michelson-Morley experiment, which was originally proposed by Maxwell as a way to determine the Earth's speed through the aether. In brief, the experiment consisted in splitting a ray of light into two perpendicular beams, where one ray travels in the same direction as the motion of the Earth and the other perpendicular to it. Assuming that both beams travel at the same speed, if the beams are then reflected at the same distance, one will return slightly earlier than the other (because it is travelling in the same direction as the rotation of the Earth). The difference in speed should, therefore, correspond to the speed of the Earth through the aether. However, when Albert Michelson (1852-1931) and Edward Morley (1838-1923) performed this experiment, they found that regardless of how precise the experiment was made, no difference could be observed for the two light beams. This experiment, among other things, proved that the luminiferous aether did not, in fact, exist. Consequently, the well-established wave theory was put into doubt.

2.4 Introducing light quanta

Towards the end of the 19th century, scientists studying thermodynamics tried to better understand the relationship between an object's temperature and light emission. In other words, scientists knew that objects at room temperature emit radiation at wavelengths far greater than those we can actually see, but they also knew that if the object was sufficiently heated (up to temperatures of around 600 to 700ºC), it would start emitting light in wavelengths we could actually perceive, starting from a dull red and finishing with a bright white. The objective was to better understand how one aspect was related to the other.

As this subject was intrinsically related to the absorption and emission of radiation, scientists realized that experimentation would be made easier by an object that absorbs and emits all radiation incident upon it (i.e. a blackbody). There are a few materials that come close to being ideal blackbodies, such as charcoal or black velvet, but the most practical example is a hole leading into a closed box. Taking this into consideration, both the experimentation and the mathematical interpretation were based upon this last model.

One of the first attempts at understanding this relationship was made in 1899 by German physicists Otto Lummer (1860-1925) and Ernst Pringsheim (1859-1917). Their contribution was published in an article by the German Physical Society, and it consisted of groundbreaking experimental data showing the light emissions of a blackbody. This important data is presented in a graph that displays the radiance as a function of wavelength. Furthermore, the graph presents three curves with three chosen temperatures: 1377º, 1087º and 836.5ºC. These three values indicate that the higher the temperature, the more prominent the curve and the smaller the maximum wavelength, as stated by Wien's displacement law.[6]

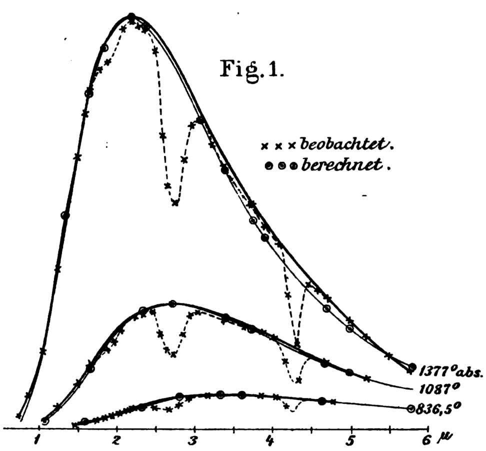

Figure 4 Lummer's and Pringsheim's results for the radiance versus wavelength (the crosses represent the observed values and the dots, the calculated values). Extracted from *Verhandlungen der Deutschen Physikalischen Gesellschaft im Jahre 1899* (February 1899, page 34) <https://forgottenbooks.com/it/readbook/VerhandlungenderDeutschenPhysikalischenGesellschaftimJahre>

The data provided by Lummer and Pringsheim was very helpful to physicists trying to develop the theoretical equations behind these results, as it provided a clear picture of the shape the mathematical function must have. One of the first attempts at describing this graph

[6] Wien's displacement law was discovered in 1893 by Wilhelm Wien (1864-1928), and it was used by Lummer and Pringsheim to make a few calculations prior to experimentation. It states that the maximum or peak wavelength of a blackbody is inversely proportional to its temperature, and that the product of these two numbers equals a constant of proportionality with a value of $\lambda_{max}T = 2.898 \times 10^{-3}$ m·K.

was the Rayleigh-Jeans Equation, an expression developed by Lord Rayleigh (1842-1919) and James Jeans (1877-1946). Their approach consisted in applying the known laws of classical physics, particularly the use of electromagnetism by Maxwell and statistical thermodynamics by Boltzmann, to describe the radiance of a blackbody. To do this, they based their ideas upon the model of the cavity in a box, and from there they developed a method to calculate the energy density of the electromagnetic waves inside the box (i.e. the energy of the radiation per unit volume), as this was directly related to the radiance. The method mentioned involved using the laws of electromagnetism to calculate the number of modes of oscillation inside the box, and then apply statistical thermodynamics to determine the average energy per mode. The result from this operation allowed them to obtain the total energy of the system, which they then divided by the volume so as to obtain the total energy density. Now knowing this value, Rayleigh and Jeans were able to complete their equation, which should, in theory, follow the same curves as the values obtained by Lummer and Pringsheim. However, disaster came when they realized that when they plotted their equation the results did not match the observed experimental data at all. It is fair to say that the Rayleigh-Jeans equation predicted quite accurately the results for longer wavelengths, but for shorter wavelengths the equation implied that as $\lambda \longrightarrow 0$, the radiance approaches infinity. This disagreement between the experimental observations and the theoretical prediction was later called the ultraviolet catastrophe, and it indicated that something was fundamentally wrong with the known laws of classical physics.

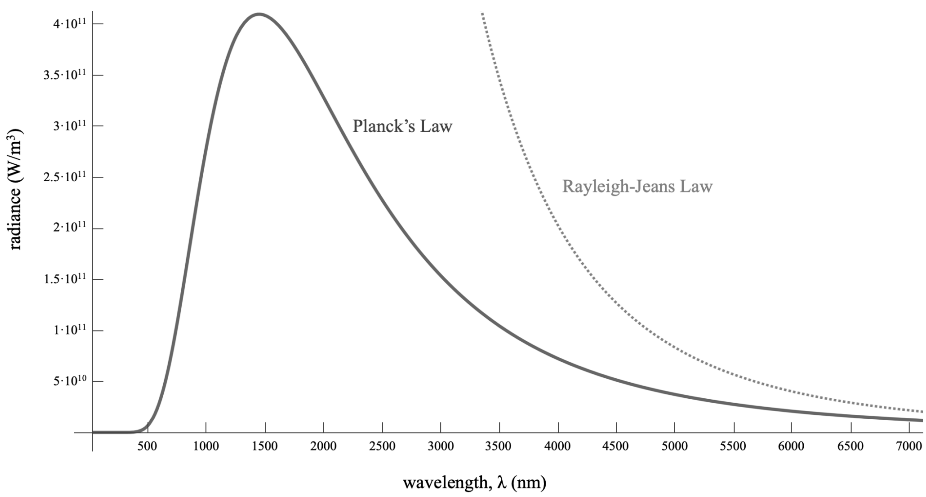

Figure 5 Plot of the Rayleigh-Jeans equation and Planck's equation for blackbody radiation when the absolute temperature equals 2000 K. Own work.

Many scientists tried working on the ultraviolet catastrophe, but a definite solution was not found until the year 1900, namely by German physicist Max Planck (1858-1947). Planck realized that the fundamental problem with the Rayleigh-Jeans equation was that it implied that as $\lambda \longrightarrow 0$, the number of modes per unit volume approached infinity, and with that, the total energy. After inspecting these results, he came to the conclusion that the energy per mode, and therefore statistical thermodynamics, was at fault. For reference, classical thermodynamics states that the average energy per mode equals

$$\boxed{E = kT}$$

Where E is the average energy per mode, k is Boltzmann's constant (with a value of $k = 1.380 \times 10^{-23}$ J·K and T is the absolute temperature. Having determined the average energy was the source of error, he went on to propose that the average energy per mode must be related to the wavelength, so that as $\lambda \longrightarrow 0$, the energy per mode also approaches zero.

From here, Planck knew that he needed to find a new expression for the average energy, so he started making a few assumptions. On the one hand, he suggested that the frequency of the light emitted by a blackbody should correspond to the frequency of the oscillators, in other words, the atoms of the blackbody in movement. On the other hand, he said that the energy of the radiation was proportional to its frequency, which meant that higher frequencies have more energy than lower frequencies. This being established, he was finally able to find an expression for the average energy, which is written as

$$\boxed{E = nh\nu}$$

Where E is the energy, n is an integer, $\nu$is the frequency and h is Planck's constant (with a value of $h = 6.626 \times 10^{-34}$ J·s). The fact that this expression is multiplied by an integer signifies that in order for the expression to work, Planck needed to assume that the energy could only take on a discrete set of values.

This had huge implications because it essentially meant that energy was quantized. In other words, Plank's equation concluded that energy was not continuous, as was previously thought, but rather, it came in small, finite amounts called quanta. Strangely enough, Planck's

hypothesis of the quantization of energy was able to successfully solve the ultraviolet catastrophe and generate new graphs that matched perfectly with the experimental data.
Despite this, by assuming energy could only be emitted or absorbed in discrete lumps, Planck had accidentally created an atomic theory for light, which had long been demonstrated to be a wave. To justify this incoherent result, as Planck himself was a believer of the wave theory, he explained that these apparent particles of light were just his mathematical way of providing a solution to the blackbody problem, but not actually a property of reality. After his discovery, he went on to make huge efforts to reconcile his results with classical physics, but he failed miserably. A few years later, in a letter to one of his colleagues, Robert Wood (1868-1955), he reflected upon his actions and said:

> Briefly summarised, what I did can be described as simply an act of desperation. By nature I am peacefully inclined and reject all doubtful adventures. But by then I had been wrestling unsuccessfully for six years (since 1894) with the problem of equilibrium between radiation and matter and I knew that this problem was of fundamental importance to physics; I also knew the formula that expresses the energy distribution in the normal spectrum. A theoretical interpretation therefore had to be found at any cost, no matter how high. It was clear to me that classical physics could offer no solution to this problem and would have meant that all energy would eventually transfer from matter into radiation. In order to prevent this, a new constant is required to assure that energy does not disintegrate. But the only way to recognise how this can be done is to start from a definite point of view. This approach was opened to me by maintaining the two laws of thermodynamics. The two laws, it seems to me, must be upheld under all circumstances. For the rest, I was ready to sacrifice every one of my previous convictions about physical laws (Planck, 1931: p. 339).

Despite Planck's controversial ideas on the nature of light, the scientific community accepted that his results were a product of the inaccuracies of his model, and that a better explanation using classical physics would soon be found. However, new experiments at the beginning of the 20th century would demonstrate that Planck's ideas were not so far-fetched.

In 1887, German physicist Heinrich Hertz (1857-1894) first proved Maxwell's ideas on electromagnetism by artificially generating electromagnetic waves. Although his contributions went towards solidifying the known laws of classical physics, he ironically and unintentionally discovered one of the experiments that would become most favourable towards the quantum theory. This experiment was the photoelectric effect, and it suggested that shining high frequency light on a metal surface would provide enough energy to set the electrons on the metal free.

Even though Hertz was puzzled by this phenomenon, he eventually decided not to study it further, so the scientific explanation was left for other physicists to uncover. The first step towards unveiling the mysteries of the photoelectric effect was made after the discovery of the electron by Joseph Thomson (1856-1940), when it was rightfully pointed out that the emission of negative charges was caused by these particles. Further research into the effect was made by one of Hertz's students, Phillip Lenard (1862-1947), who became very interested in it and made important remarks about it.

To study the photoelectric effect in detail, Lenard built an apparatus where he placed two electrodes, a cathode and an anode, facing each other inside a glass tube. To better allow the flow of electrons, he then created a vacuum inside the tube and proceeded to irradiate the cathode with high frequency light. The result from this set-up was the establishment of a current due to the electrons being ejected from the cathode and reaching the anode. From this first observation, Lenard was able to conclude that the electric current was a consequence of the cathode being irradiated, as if the set-up was left in the dark, no current could be observed. Later, he added a battery to the system, which allowed him to introduce an adjustable potential difference between electrodes. By also varying the intensity and frequency of the irradiated light, Lenard was able to make a few important observations.

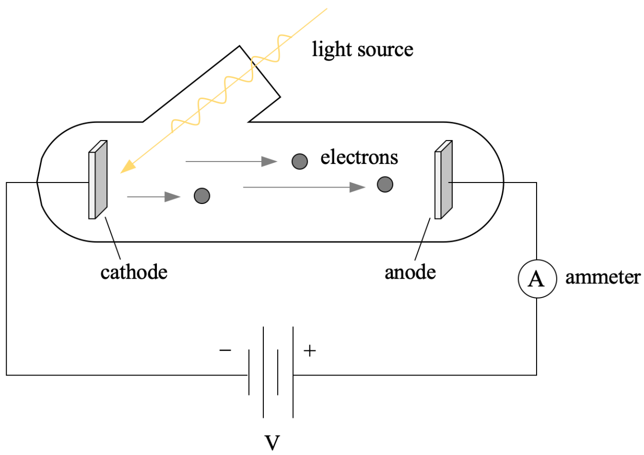

Figure 6 Schematic diagram of Lenard's apparatus for the photoelectric effect. Own work.

First, he found that the current is proportional to the intensity of the light (i.e. the more intense the light, the stronger the current), and that this current is established immediately after the emission of light. Then, he observed that the emission of electrons is dependent on the frequency of light, not the intensity. This meant that electrons are only emitted if a certain frequency is surpassed, a frequency known as the threshold frequency, which varies depending on the metal the cathode is made from. Lastly, he noticed that when the anode is positive with respect to the cathode, the current is unchanged (as all electrons are attracted to the anode and can, therefore, reach it). When the opposite situation occurs, the anode being negative with respect to the cathode, the current is slowly decreased until at a certain point, no current can be detected (as all electrons are repelled from the anode and cannot, therefore, reach it). This point of no current is called the stopping potential, and Lenard detected that it was the same for all light intensities.

Despite Lenard's remarkable results, once again classical physics could not account for the anomalies presented in the experimental data. How could it be possible that a high frequency low intensity light can eject electrons, but a low frequency high intensity light cannot? Classically, it would have been expected that light of higher intensity (i.e. light whose waves are larger in amplitude) should have enough energy to establish a current, regardless of the frequency. However, as observed, this was not the case. Another oddity observed by Lenard was the immediate creation of a current after switching on the light source. Again, this was in disagreement with the known theories, which would have predicted that the emission of electrons was due to thermal causes and, therefore, that some time should have passed before the current was established. If the thermal theory was correct, this would have also meant that high intensity light should have provided the electrons with more kinetic energy. Macroscopically, this would have signified that high intensity light should have a different stopping potential from low intensity light. But once again, this does not agree with the experimental results.

Finally, in 1905, Albert Einstein (1879-1955) was able to provide a solution that succeeded in explaining the photoelectric effect. Einstein knew about Plank's quantization approach to the ultraviolet catastrophe, and thought that, perhaps, his ideas were not so preposterous. He applied the same assumptions Planck desperately made, and went on further to say light itself is quantized. In other words, Einstein explained that light comes in discrete packets of energy called *lichtquanten*, which is German for light quantum.[7] These energy bundles, he thought, should follow the relation Planck found ($E = hv$) while travelling at the speed of light.

[7] The commonly known term for a particle of light, a photon, was later introduced in a letter Gilbert Lewis (1875-1946) wrote to *Nature* in 1926.

Taking this new model of light into account, Einstein explained the photoelectric effect quite simply. On the one hand, he reasoned that each light quantum is absorbed by only one electron, and thus transfers all its energy. This would perfectly explain why Lenard found that the emission of electrons was dependent on the frequency of the light, because the energy of each light quantum (based on its frequency) is given to the electron. Furthermore, this justifies that the reason no electrons are emitted under a certain frequency is because the energy light provides the electron is not enough to allow it to leave the metal. Additionally, the fact that a light quantum provides its energy to an electron means that it immediately gains sufficient kinetic energy to leave the metal and create a current, rather than after a few minutes because of thermal causes. On the other hand, the intensity of a light source is linked to the number of quanta that fall on the metal surface. This means that the higher the number of light quanta, the more electrons are excited and the stronger the current generated. Simultaneously, this proves that the intensity does not have any relationship with the stopping potential, as this has to do with the kinetic energy of the electrons, and not their number.

After Einstein published his theoretical analysis of the photoelectric effect, a series of experiments conducted by American physicist Robert Millikan (1868-1953) confirmed his ideas were, in fact, correct. It was now clear that light also could exhibit a particle-like behaviour, as this experiment could not be explained in terms of waves. In Einstein's words:

> Also, without going deeper into any theoretical consideration, one sees that our theory of light is unable to explain certain fundamental properties of the phenomenon of light. Why does whether a particular photochemical reaction proceeds or not only depend on the color of the light and not on its intensity? Why are the short wave rays universally more effective chemically than long wave ones? Why is the speed of photoelectrically emitted cathode rays independent of the intensity of the light? Why does it require a higher temperature and therefore higher molecular energy for the radiation emitted from a body to exhibit short wave properties? In its current form the wave theory gives no answer to any of these questions. [...] The basic property of the wave theory that brings these difficulties with it seems to me to lie in the following. While in the kinetic molecular theory there exists an inverse process for every process, e.g. for every molecular collision, this is not the case under the wave theory for elementary radiation processes. An oscillating ion radiates, according the theory we accept, a spherical wave that propagates outward. The reverse process, as an elementary process, does not exist. A spherical wave propagating inward is indeed mathematically possible but it needs a colossal number of emitting elementary structures for its precise realization. Therefore the process of the emission of light, as such, does not have the character of reversibility. It is here, I think, that our wave theory does not

> give the correct result. It seems that, in relation to this point, the emission theory of Newton holds more truth than the wave theory (Einstein, 1909: pp. 6-7).

The particle theory of light had successfully been revived, and physicists were confused. Further corroboration for Einstein's ideas was presented by Arthur Compton (1892-1962), who was studying the energy difference between an incident beam of x-rays and a scattered beam (i.e. scattered rays presented a lower wavelength than the original incident ray). By applying the particle model, he was able to interpret the scattering as a collision between the incoming photons and the electrons of the scattering material. This allowed him to obtain an expression for the difference in wavelength using the known laws of conservation of momentum and energy. This expression goes as follows

$$\lambda_2 - \lambda_1 = \frac{h}{mc}(1 - cos\theta)$$

Where λ_2 - λ_1 is the difference in wavelength, *h*/*mc* is the Compton wavelength λ_c (with a value of $\lambda_c = 2.426 \times 10^{-3}$nm for electrons), and θ is the scattering angle. It was then evident that the wavelength of the scattered photons had to be lower, because the collision transferred part of its energy to the electrons of the material. Compton later verified his hypothesis experimentally, and this phenomenon of scattered x-rays came to be known as the Compton effect. The fact that a particle collision model could perfectly explain the difference in wavelengths helped to rule out all theories that predicted that light itself was not quantized, but rather the matter that absorbs it. It was once again proven that light quanta was a real phenomenon beyond Planck's inaccuracies.

As more and more experiments agreed with the corpuscular theory, a definitive explanation for the nature of light seemed to be further out of reach than ever. What began as a simple quest to understand what light was made of, developed into a fundamental crisis where two utterly different models were considered and proven to work. How could we account for the fact that light behaves in two separate ways simultaneously? Why is it more convenient to use one model at times rather than the other? How can we unify or neglect these well-established views? It seemed as though the debate over the nature of light had generated more questions than it had answered.

3. Two classically exclusive pictures of reality

After the introduction of the quantization of light, it was clear that the nature of light was a phenomenon that was way more complex than originally thought. Scientists could not understand how it was possible for two such different physical models (particles and waves) to explain light together. As Albert Einstein and Leopold Infeld (1898-1968) stated:

> It seems as though we must use sometimes the one theory and sometimes the other, while at times we may use either. We are faced with a new kind of difficulty. We have two contradictory pictures of reality; separately neither of them fully explains the phenomena of light, but together they do! How is it possible to combine these two pictures? How can we understand these two utterly different aspects of light? It is not easy to account for this new difficulty. Again we are faced with a fundamental problem (Einstein and Infeld, 1938: p. 278).

From all the theories that have been developed on light, we can see that depending on the experiment, it is more favourable to use a particle or a wave model. For instance, the double slit experiment can easily be accounted for by using the analogy of a water wave, but it would be rather difficult to explain it in terms of quanta or corpuscles. Before reaching a deeper understanding of the ambiguous nature of light, I believe it is necessary to examine the key experiments for each model of light: the double slit experiment for waves and the photoelectric effect for quanta. Performing these experiments will not only help corroborate the original ideas, but will also prove that these two pictures of light do indeed exist simultaneously.

3.1 The double slit experiment

As said in the last section, at the beginning of the 19th century Thomas Young carried out his famous double slit experiment, which goes to prove that light is a wave. Although his original set-up differs from the known modern version, I performed the latter, as it is easier to visualize and the conclusions reached are practically identical. To execute this version, a light beam has got to pass through two small parallel slits, and the resulting light can be observed on a screen placed a certain distance away.

My experimental set-up consisted of a laser beam of 632.8 ±0.1 nm in wavelength (i.e. a red coloured light beam), a filter with four double slits of different sizes, and a millimetre paper sheet to act as a screen. Following the modern double slit experiment, I switched on and pointed the laser beam towards one of the four pairs of slits. Once everything was lined up, I observed the light obtained on the screen and managed to extract three results that favoured the wave theory of light.

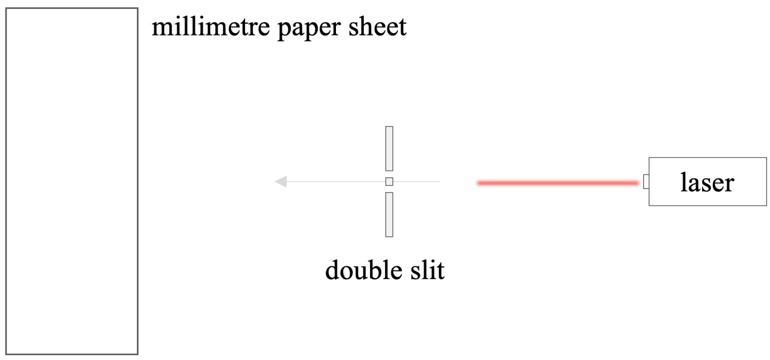

Figure 7 Schematic diagram of my experimental set-up for the double slit experiment. Own work.

3.1.1 A pattern characterized by interference and diffraction

The first piece of evidence that indicates light does, in fact, exhibit wave-like behaviour is the pattern I was able to observe on the screen.

As the beam of light can only shine through the two slits, if we adopted a particle model, we would expect to see two parallel bright fringes of light along the screen. This is due to the fact that only the particles that follow a trajectory within the slits are able to pass through them and impact the screen. Naturally, the particles that do not travel inside these boundaries will be blocked by the material part of the slit and, thus, will not shine through.

However, when I performed this experiment, I obtained the same result as Young did in the 1800s: an interference pattern. This is a result of the application of a wave-like model of light, as the pattern is a direct consequence of constructive interference, destructive interference and diffraction. When the beam of light is met with the double slit, these two parallel lines act as point sources (as explained by Huygens' principle) for a series of spherical waves that travel outward in all directions. Given that there are two sources, the waves produced will inevitably have to interact with one another, thus constructively and destructively interfering. The result from this interaction between light waves is a pattern of bright and dark fringes extending beyond the direct limits of the aperture of the slits.

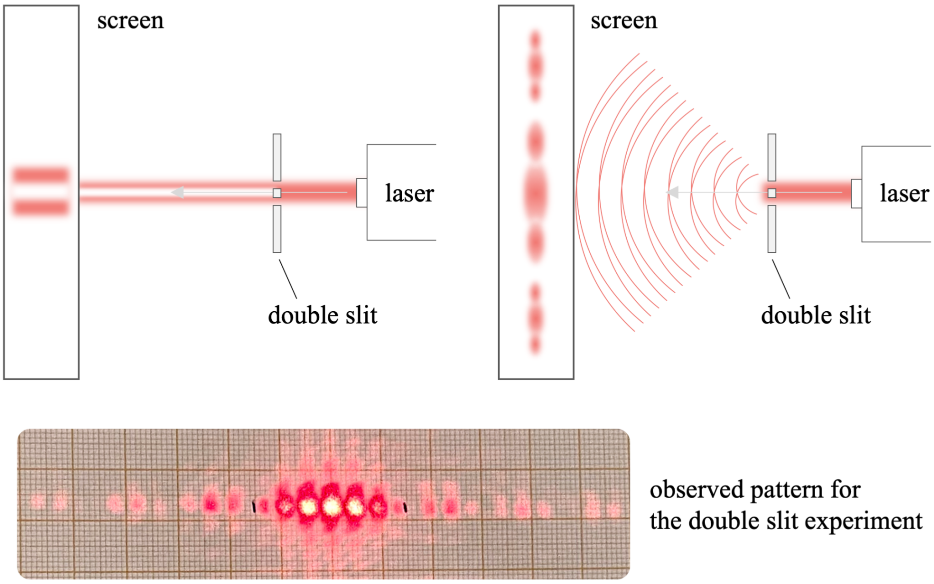

Figure 8 Double slit experiment if light was a particle (left) and if light was a wave (right). The interference pattern (bottom) agrees with the right picture, thus providing a clue that light is a wave. Own work.

3.1.2 Finding and verifying the value of λ

As I mentioned above, the light waves coming from each slit overlap and interfere with one another. The result of these interferences is the pattern observed on the screen: the bright spots are a result of constructive interference, and the dark spots are a result of destructive interference. From these alternating fringes we can infer that depending on the angle between the centre of the screen and a given point, the superposition between waves can result in an increase or decrease of intensity (i.e. brighter or darker fringes).

Given a point P in the screen, the brightness of that spot is going to depend on the two point sources: S_1 and S_2. Since these sources are separated by a distance d in between slits, if we trace the path lengths $\overline{S_1P}$ and $\overline{S_2P}$, we will realize that there is a small path-length difference between slits. This difference can be expressed as $d\sin\theta$, where the angle θ is of the same magnitude as the one between the slits, the central point and P.

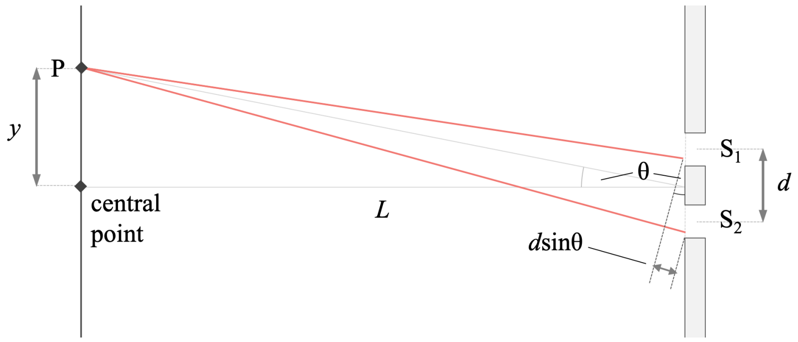

Figure 9 Geometry of the double slit experiment. Own work.

Depending on the value of the path difference, *P* will exhibit constructive or destructive interference. If the path-length difference is equal to an integer number of wavelengths, the individual waves will sum up their amplitudes to display interference maxima (i.e. a bright spot). However, if the path-length difference is equal to an integer number of wavelengths plus half a wavelength, the individual waves will cancel each other out to display interference minima (i.e. a dark spot). Furthermore, if the path length difference is equal to an intermediate value between interference maxima and minima, the light intensity will be dimmer than the bright spots, but not as dim as the dark ones. Mathematically, we can express the ideas stated as

$$d sin\theta_m = m\lambda$$

for interference maxima, and

$$d sin\theta_m = (m - \frac{1}{2})\lambda$$

for interference minima. It is important to note that the bright fringes of the interference pattern are numbered outward, starting from the central maximum $m = 0$. This integer value is what is designed in the equations as m.

As further proof that light is a wave, we can use these interference-based equations to find the wavelength of the laser beam. As noted before, the value for the wavelength is already known to be 632.8 ±0.1 nm, so the objective is to try to obtain a value as close as possible.

However, before using the above equations, because it is always easier to measure distances than angles, we will introduce a few changes. The angle between the slits, the central maximum and the *m*th fringe can also be expressed in terms of the distance y_m and the length L, so that

$$tan\theta_m = \frac{y_m}{L}$$

Because for small angles $sin\theta_m \approx tan\theta_m$ we can express the equation for the interference maxima as

$$y_m = \frac{m\lambda L}{d}$$

Rearranging terms we get

$$\boxed{\lambda = \frac{y_m d}{mL}}$$

From here, I measured the length between the slit and the screen L = 192.4 ±0.1 cm and the distance between the central maximum and the first five bright fringes (m = 1 to m = 5). The separation between slits was given by the filter d = 0.250 ±0.001 mm. Expressing the values in nanometres and substituting them into the equation, I obtained the following results:

m	**λ (in nm)**	**Relative error**
1	650 ±70	10.4%
2	620 ±40	5.7%
3	610 ±20	4.0%
4	630 ±20	3.0%
5	620 ±20	2.6%
Average	630 ±70	10.8%

Table 1 Wavelength values obtained. Own work.

The average value for the wavelength is $\bar{\lambda}$ = 630 ±70 nm. Since it comes within the limits of experimental error, we can conclude that our measures are correct (1.1% deviation from theoretical value), but nonetheless imprecise. The relative error percentages are quite high due to difficulties in the measurement of y distances, as the only reference available was the millimetre paper sheet and it was sometimes difficult to decide where the maximum points exactly landed. Despite this, it is safe to assume that these interference-based equations apply.

3.1.3 Locating points of maximum and minimum intensity

Finally, I will further analyse the interference pattern to prove that it not only agrees with the theoretical predictions of a wave's propagation (as done in section 3.1.1), but also, with the mathematical prediction for interference maxima and minima.

To do this, I will start by studying the intensity variation of the pattern as a function of the angle. The graph obtained when plotting these parameters for a double slit is the combination of the intensity graph that would be obtained by only considering one of the two slits (i.e. a single slit intensity pattern) and the graph we would obtain with the double slit. In other words, the graph will display intensities, maximum points and minimum points characteristic of both types of diffraction.

An intensity graph produced by a single slit would consist of a broad central intensity maximum, and two small secondary peaks of much lower intensity. Therefore, it is no surprise to observe that the double slit graph adapts this shape into its interference pattern, the only difference being the equally spaced maximums and minimums within the intensity maximums of the single slit pattern.

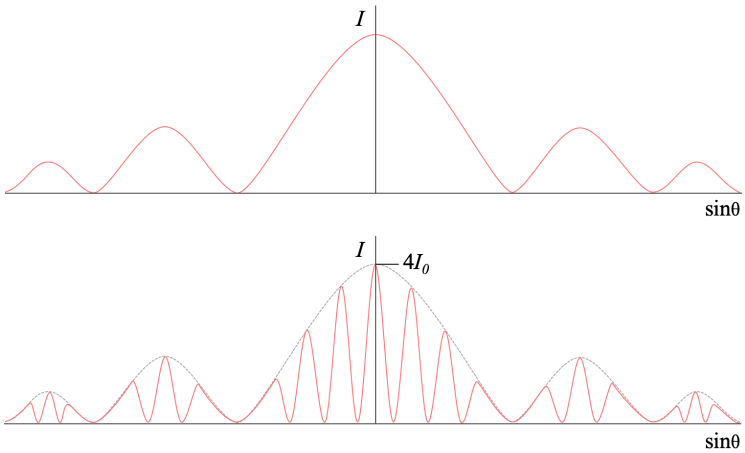

Figure 10 Intensity versus angle for the single slit (top) and the double slit (bottom).[8] My interference pattern corresponds with the bottom graph. Own work.

[8] The graph for the intensity of the double slit has a peak at the central maximum of $4I_0$, where I_0 is the intensity of each individual slit. Naturally, you would infer that if I_0 is the intensity of one slit, the central maximum of the double slit experiment would have an intensity of $2I_0$. However, it is known from classical physics that the intensity at a given point is proportional to the square of the amplitude, so that $I \propto A^2$. Therefore, because the amplitude of each wave a is going to constructively interfere in the central maximum ($A = 2a$), the total amplitude will be $4a^2$. Given that the intensity is proportional to the amplitude squared, its value at the central maximum is $4I_0$ and not $2I_0$.

These successive maximums and minimums produced by the double slit can be located precisely if the equations from the last section are used. By assuming $sin\theta_m \approx tan\theta_m$ for small angles, we were able to modify the equation for interference maxima and obtain an expression for y_m

$$y_m = \frac{m\lambda L}{d}$$

This equation allows us to obtain the distances between the central maximum and the *m*th fringes we want. To simplify things, I will only be calculating the positions for the three first bright fringes $m = 1$ to $m = 3$. Knowing that the wavelength value is $\lambda = 632.8 \pm 0.1$ nm, the length between the slit and the screen is $L = 192.4 \pm 0.1$ cm and the distance between slits is $d = 0.250 \pm 0.001$ mm, we can calculate the distances to be:

m	***y* (in mm)**	**Relative error**
1	4.87 ±0.02	0.5%
2	9.74 ±0.05	0.5%
3	14.61 ±0.07	0.5%

Table 2 Distances between the central maximum and the *m*th fringe. Own work.

As we can see, because we dealt with more precise values, the relative error with respect to the wavelength calculations is much lower. Also, if we compare the results with the actual positions in the millimetre paper sheet, we find that they match up quite accurately.

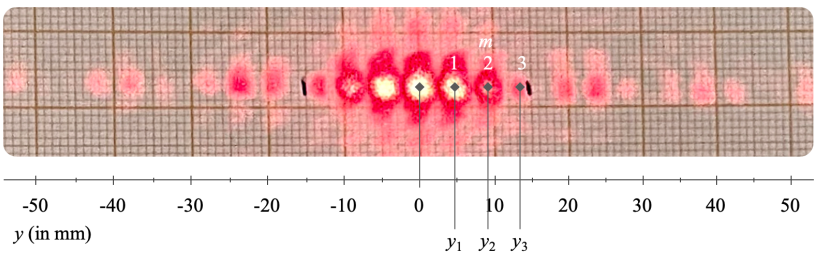

Figure 11 Positions of points $m = 1$, $m = 2$ and $m = 3$ on the interference pattern. Own work.

Furthermore, if we look closely at the interference maxima, we will realize that the third bright fringe ($m = 3$) is much less intense than the previous two. This significant decrease in brightness is due to the fact that, as I mentioned before, the double slit pattern is modulated by the single slit pattern. This results in a dimmer fringe, because the spot where an intense maximum should be found, has been muted by the closely-located first single slit minimum. To further prove this point, I will use the equation for single slit interference minima to locate the position of the first minimum. Generally, zero intensity points for single slit diffraction are given by

$$a \sin\theta_m = m\lambda$$

This equation closely resembles the one for double slit interference maxima, all values being the same except for the distance between slits *d*, that is now replaced for the amplitude of one slit a. Despite this, I must point out a slight difference between the *m* value of this equation and the one for the double slit: in the expression above, this letter represents the *m*th dark fringe, whereas in the double slit equation, it represents the *m*th bright fringe. As it is easier to measure distances than angles, we are again going to use the small angle approximation $\sin\theta_m \approx \tan\theta_m$ to transform our expression into

$$y_m = \frac{m\lambda L}{a}$$

Knowing that the wavelength of the laser beam is λ = 632.8 ±0.1 nm, the length between the slit and the screen is *L* = 192.4 ±0.1 cm and the amplitude of one slit is *a* = 0.08 ±0.01 mm, we can calculate the position of the first minimum to be

Result	Relative error
15±2 mm	12.8%

Table 3 First single slit minimum

Judging by the results, this measurement is quite imprecise. However, unlike the lambda calculations, there cannot be many experimental mistakes (only *L* was measured), so the only possible explanation is that the filer value *a* is not as accurate as expected (the filter was not in excellent condition). Despite this, the value does fall closely to the third interference maximum y_3 = 14.61 ±0.07 mm, which explains the decrease in brightness.

In all, we have seen that the spots we have calculated via wave-based equations have matched up with the observed fringes. Once again, it has been demonstrated that a wave model of light is necessary to explain experiments such as the double slit experiment.

3.2 The photoelectric effect

Despite the convincing evidence above, there are a few experiments on light that can only be understood if the quantization of light is considered to be true. One of the most important among this group of experiments is the photoelectric effect, first found in 1887 by Hertz, later studied by Lenard, and finally explained by Einstein. Considering Lenard's set-up, this experiment consists in shining a light source on a cathode so that the electrons on its surface obtain enough energy to be freed, reach the anode and produce an electric current.

My experimental set-up was composed of a white light lamp, a photoelectric device with a photoelectric cell and a voltage regulator, six coloured filters, an oscilloscope and a voltmeter. Once I had everything set up, I placed one of the six coloured filters between the light source and the photoelectric cell. By doing so, when I switched on the lamp, only certain wavelengths of light were allowed to pass through the filter and impact the surface of the cathode. After this, I observed the effects produced by illuminating the photoelectric cell with six different wavelengths, and I extracted two important results.

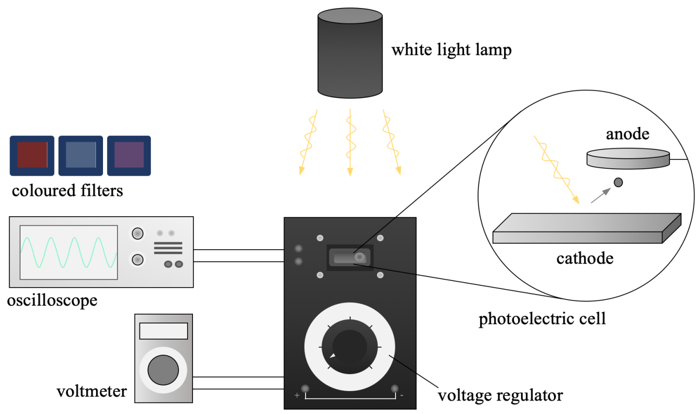

Figure 12 Schematic diagram of my experimental set-up for the photoelectric effect. Own work.

3.2.1 Photoelectrons create a current

Just like Lenard observed, as soon as the lamp was switched on, the photons that were incident on the surface of the cathode provided the electrons (or photoelectrons) with enough energy to leave the metal and generate a current upon reaching the anode.

In my case, the generated current could be observed in the oscilloscope, whose voltage versus time graph presented two important characteristics. On the one hand, the graph followed a sinusoidal shape, which is an indicator of alternating current. This result proves that the current being observed was due to the white light lamp, which was the only device plugged in other than the oscilloscope. On the other hand, depending on the coloured filter applied, the amplitude of the sinusoid drastically changed (while not applying any additional voltage and maintaining the light intensity constant). For instance, when the red filter was applied, only wavelengths longer than 620 nm could reach the metal surface, and, therefore, only a few sufficiently energetic electrons reached the anode to create a current. However, when the blue filter was applied, since wavelengths between 450 and 490 nm could reach the surface, many electrons had enough energy to leave the cathode and reach the anode. Given that the current depends on the number of electrons reaching the anode, few electrons will create a small current (and thus a sinusoid with a smaller amplitude), whereas many electrons will create a strong current (and thus a sinusoid with a greater amplitude). This observation is clear proof that the energy of each photon is related to its frequency because if light from different wavelengths had the same energy, the same amount of electrons would reach the anode regardless of the filter, and thus the sinusoid would remain the same under all circumstances.

Classical physics explains that the larger the amplitude, the more intense and energetic a light wave is. However, in the experiment, light intensity remained constant while, according to the oscilloscope, the electron kinetic energy varied. This means that this value is independent of the intensity, and, rather, varies with the frequency. The idea of relating the energy and frequency of light was first proposed by Planck in his quantization of light. Therefore, this is the first piece of evidence that points to the need of light quanta or photons.

3.2.2 Plotting Millikan's graph and determining Planck's constant

As we saw in section 2.4, in 1905, Einstein explained the photoelectric effect in terms of light quanta that transferred all their energy to the electrons in the metal. This energy exchange would then allow the electrons to leave the metal and travel freely through space. However, Einstein not only analysed the photoelectric effect from a quantum perspective, but also justified his ideas mathematically. To do so, he started by stating that the total energy of the excited electron is equal to the energy lost as the electron leaves the metal plus its kinetic energy. By considering W_0 as the minimum energy required to extract the electron from the metal, we can write the maximum kinetic energy of the electron K_{max} as

$$K_{max} = E_{elec} - W_0$$

Where E_{elec} is the total energy of the electron. Knowing that the particle's energy is provided by light, and that light's energy is quantized, we can express the total energy of the electron as $E_{elec} = hv$.[9] Substituting this into the equation above gives

$$K_{max} = hv - W_0$$

However, the maximum kinetic energy is quite difficult to measure experimentally. For this reason, it is preferable to measure the stopping potential instead. In a photoelectric cell, when the anode is made negative with respect to the cathode, the current slowly starts decreasing until it is no longer detected. When this happens, the stopping potential is said to have been reached because no electrons have enough kinetic energy to reach the anode and start the current: they are all repelled. Therefore, the maximum kinetic energy of an electron K_{max} corresponds to the stopping potential V_0. In other words

$$eV_0 = K_{max} = hv - W_0$$

Where e is the electron charge with an approximate value of $e = 1.60217662 \times 10^{-19}$C. This expression indicates that the stopping potential does not depend upon the intensity of the light, but rather, its frequency. Once Einstein found this equation for the photoelectric effect, he realized that it suggested that the graph of the stopping potential versus frequency was a straight line of slope h/e. This prediction was later tested by Robert Millikan as a way to experimentally determine Planck's constant.

In order to prove the particle-like nature of light, I recreated this experiment and found Planck's constant. After switching on the lamp and observing the current in the oscilloscope, I measured the stopping potential of each individual filter and later proceeded to plot the graph given by the above formula. In order to measure the stopping potential, I placed the filters and, once I detected the current in the oscilloscope, I varied the voltage until a current could no longer be appreciated. Once I had found the stopping potential, I measured its value with a voltmeter and took note of it. I took three separate measures of the stopping potential for each filter, as the oscilloscope is very sensitive to background noise and was sometimes difficult to manage. The results I obtained are listed in the following table.

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[9] It should be noted that we are purposely neglecting the electron's thermal energy at room temperature, as it is minimal compared to hv.

Filter wavelength range (in nm)	Stopping potential (in V)				Relative error (average)
	1	2	3	average	
red: 620 - on	0.032 ±0.001	0.036 ±0.001	0.032 ±0.001	0.033 ±0.002	5.3%
orange: 575 - 610	0.142 ±0.001	0.129 ±0.001	0.117 ±0.001	0.129 ±0.008	6.5%
yellow-green: 530 - 570	0.220 ±0.001	0.208 ±0.001	0.226 ±0.001	0.218 ±0.007	3.1%
blue-green: 470 - 520	0.355 ±0.001	0.359 ±0.001	0.370 ±0.001	0.361 ±0.006	1.6%
blue: 450 - 490	0.421 ±0.001	0.400 ±0.001	0.414 ±0.001	0.412 ±0.008	1.9%
violet: 380 - 450	0.409 ±0.001	0.410 ±0.001	-	0.410 ±0.001	0.1%

Table 4 The stopping potential according to each filter. Own work.

It should be noted that the violet filter did not work properly. The filter was too dark, which made it difficult for light to shine through and to obtain the values for the stopping potential. After increasing the intensity by placing the light lamp closer to the filter, I was only able to register two values. These, as will be shown later, do not correspond to the expected value for its wavelength.

After obtaining the values for the stopping potential, I needed to choose the wavelengths. Given that the experiment was done with filters, there are a variety of wavelengths to consider. More specifically, each filter had an associated graph where you could appreciate the transmission coefficient per each wavelength.[10] As I needed one wavelength value per filter, I considered three different criteria and selected three different wavelengths per filter. Later, I plotted three different graphs, one per each criterion, and evaluated which best predicted the *h* slope. The three criteria chosen are the following:

1. The wavelength value corresponds to the peak of the curve. It is the wavelength with the highest transmission coefficient.
2. The wavelength value corresponds to the shortest wavelength from the middle point of the curve. This allows us to consider the most energetic light while ensuring that the transmission coefficient is still significant.

[10] The graphs for each individual filter can be found in the annex.

3. The wavelength value corresponds to the shortest wavelength from one fourth of the distance to the peak of the curve. This last criterion considers the lowest transmission coefficient, but the most energetic light.

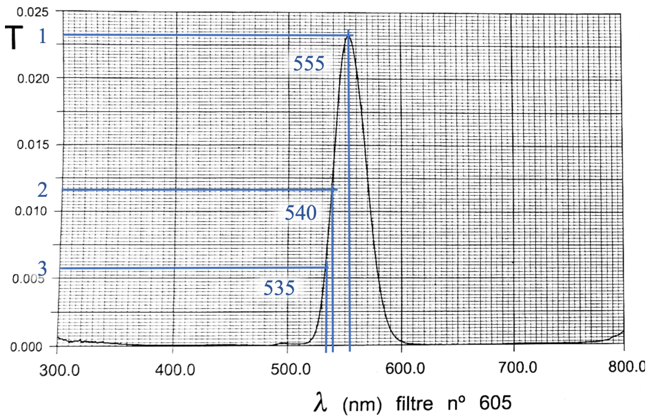

Figure 13 Example of the three criteria marked on the graph for the yellow-green filter. Edited image from graphs provided by [Programa Argó advisor], UAB.

The chosen values following each criterion are presented in the following table.

Filter wavelength range (in nm)	Chosen wavelength (in nm) with its relative error					
	Criterion 1		Criterion 2		Criterion 3	
red: 620 - on	740±5	0.8%	665±5	0.7%	650±5	0.8%
orange: 575 - 610	605±5	0.8%	590±5	0.8%	585±5	0.9%
yellow-green: 530 - 570	555±5	0.9%	540±5	0.9%	535±5	0.9%
blue-green: 470 - 520	495±5	1.0%	480±5	1.0%	475±5	1.1%
blue: 450 - 490	470±5	1.1%	455±5	1.1%	450±5	1.1%
violet: 380 - 450	440±5	1.3%	400±5	1.1%	380±5	1.3%

Table 5 Chosen wavelength according to each filter, following three criteria. Own work.

Now that I had obtained the values for the stopping potential and the wavelengths, I had to make a few calculations before plotting the graph. On the one hand, for the stopping potential, I had to multiply each average by 2 due to a systematic error in the set-up. This mistake is not associated to my measurements, it is a fault in the equipment used that has not been able to be resolved. The resulting values then had to be multiplied by *e* (the electron's charge) so that the slope of the graph represents *h* and not *h/e*. On the other hand, each wavelength has to be expressed as a frequency by converting the values from nm to m, and then following the relation between frequency and wavelength ($\nu = c/\lambda$). The values that define our graph are finally:

Filter frequencies (in 10^{14} Hz) with its relative error						**eV_0 or maximum kinetic energy (in 10^{-19}J)**	
Criterion 1		**Criterion 2**		**Criterion 3**			
4.05 ±0.03	0.7%	4.51 ±0.03	0.8%	4.61 ±0.04	0.8%	0.107 ±0.006	5.3%
4.96 ±0.04	0.8%	5.08 ±0.04	0.8%	5.12 ±0.04	0.9%	0.41 ±0.03	6.5%
5.40 ±0.05	0.9%	5.55 ±0.05	0.9%	5.60 ±0.05	0.9%	0.70 ±0.02	3.1%
6.06 ±0.06	1.0%	6.25 ±0.07	1.0%	6.31 ±0.07	1.1%	1.16 ±0.02	1.6%
6.38 ±0.07	1.1%	6.59 ±0.07	1.1%	6.66 ±0.07	1.1%	1.32 ±0.02	1.9%
6.81 ±0.08	1.1%	7.49 ±0.09	1.3%	7.9±0.1	1.3%	1.312 ±0.002	0.1%

Table 6 Filter frequencies and their corresponding maximum kinetic energy (or eV_0). Own work.

When plotting the graphs, I realized that the violet filter was way under the expected value. This caused the graphs to have a smaller slope than they should. In order to obtain the most accurate results possible, I dismissed the values for the violet filter.

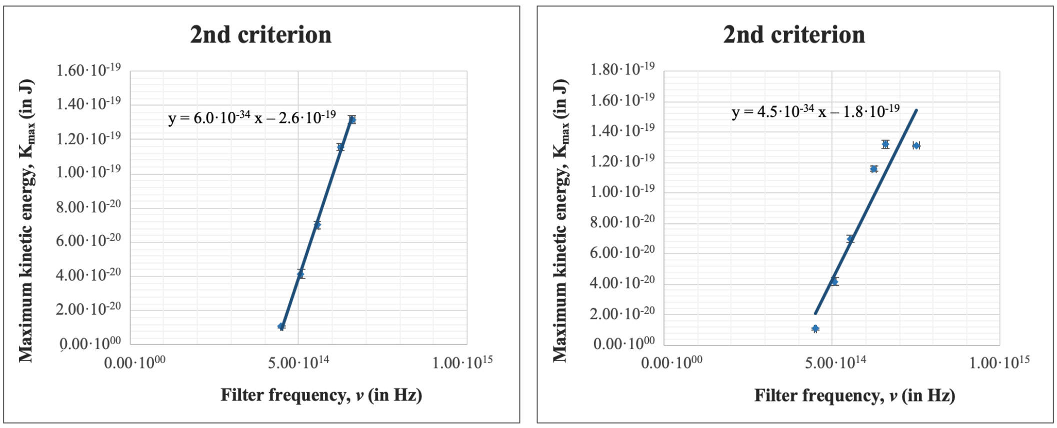

Figure 14 Comparison of the graph considering the violet filter values (right) and not considering these values (left). Own work.

The correlation coefficient of the graphs in figure 14 are R=0.999 (left) and R=0.948 (right). This goes to show the impact this single value has. Making this change, the three graphs for the stopping potential times *e* versus frequency are now presented.

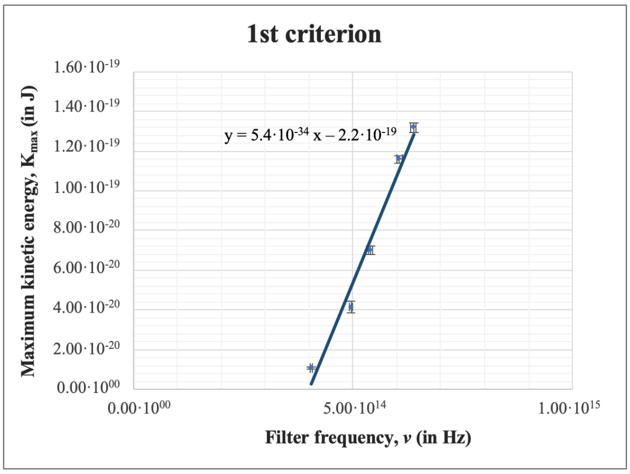

Figure 15 Plotted graph for the photoelectric effect data following the 1st criterion. Own work.

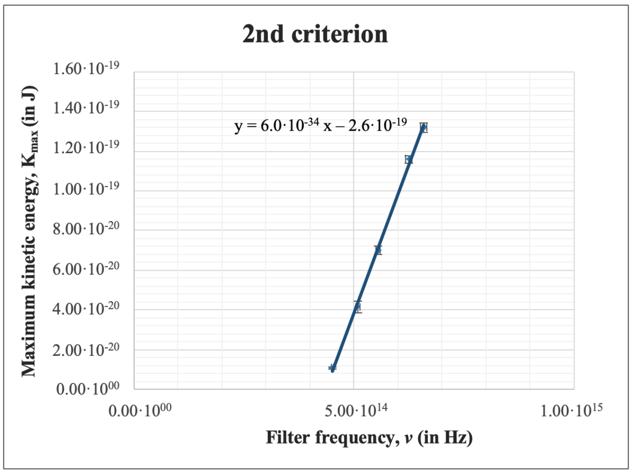

Figure 16 Plotted graph for the photoelectric effect data following the 2nd criterion. Own work.

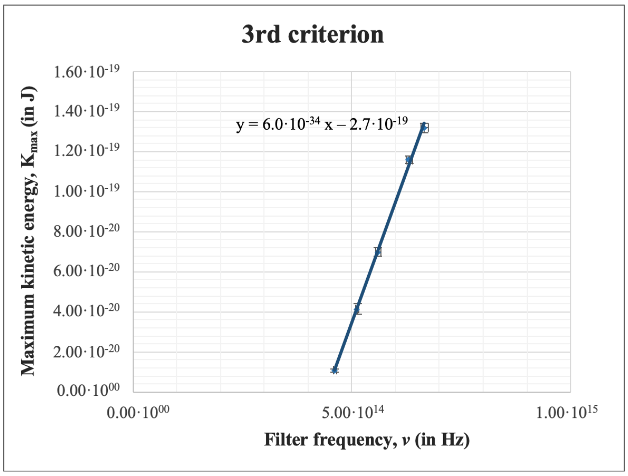

Figure 17 Plotted graph for the photoelectric effect data following the 3rd criterion. Own work.

The correlation coefficient of figures 15, 16 and 17 are R=0.988, R=0.999 and R=0.999 respectively. This is because the measuring tools were more precise than those used in the double-slit experiment. We can appreciate this through the generally low relative errors throughout the process.

The experimental results are the following:

	Criterion 1		**Criterion 2**		**Criterion 3**	
***h* (in 10^{-34} J·s)**	5.4 ±0.3	5.6%	6.0 ±0.4	6.7%	6.0 ±0.5	8.3%
ν_0 (in 10^{-14} Hz)	4.07 ±0.06	1.4%	4.33 ±0.05	1.2%	4.50 ±0.06	1.3%

Table 7 Planck's constant *h* and threshold frequency ν_0 values obtained using the three criteria, and their relative error. These values were obtained with Excel using linear regression. Own work.

Judging by these values, it seems that the 1st criterion is the least accurate of the three, and that there is almost no difference between the 2nd and the 3rd. The deviation from the theoretical values are 19% for the first criterion and 9% for both the second and the third. This means that *h* gets more accurate as shorter wavelengths are considered. This is logical, as when the stopping potential is reached, only the most energetic electrons remain. However, there seems to be no significant difference when considering the shortest wavelengths starting from the middle point or one fourth of the curve, as the slope is quite similar.

All in all, it has been demonstrated that Einstein's equation for the photoelectric effect indeed correlates to the experimental results, and that Planck's constant can be obtained. Given that we have found that the energy of the light is related to its frequency, and that Planck's constant can be determined, we can conclude that Planck's quantization approach is correct, and that quanta are a property of light. Strangely enough, light also behaves like a particle.

4. The wave-particle duality concept

In the last section, it was made evident that two different experiments involving light give out two separate ideas that apparently can not be unified. This same difficult conundrum was faced by many physicists in the early years of the 20th century, and, amongst other things, led to the creation of a new branch of physics: quantum mechanics. The new ideas developed under the premises established by Planck (namely that light comes in discrete energy bundles called quanta), helped get a better understanding of the microscopic world and the phenomenon of light. In this section, I will take a closer look at the new theories for quantum mechanics and see what they bring to the nature of light. Additionally, I will also be discussing alternative views on light so as to get a bigger picture of our current understanding of the subject.

4.1 The birth of quantum mechanics

Following the explanation of the photoelectric effect, Albert Einstein went on to conclude that light must be explained in terms of particles. However, he was unable to refute all the evidence that pointed to light being a wave. To solve this problem, he proposed that perhaps we should not attempt to refuse one of the two models, but rather accept that we must unify these two views to explain light. In his words:

> It is undeniable that there is an extended body of facts pertaining to radiation which indicate that light has certain inherent qualities that put its comprehension far from either the Newtonian emission theory of light or the view of wave theory. Hence it is my opinion that the next phase of the growth of theoretical physics will bring us a theory of light which will reveal itself as a kind of mixture of wave and emission theory. It is the purpose of the following exercise to elucidate and substantiate this position: that a fundamental change of our understanding of the nature and constitution of light is essential (Einstein, 1909: p. 1).

This idea he referred to as a "mixture of wave and emission theory" later came to be known as wave-particle duality. His new theory suggested that perhaps the classical particle and wave models are not as incompatible as previously thought. The following example might help us understand this last point.

It is known that waves diffract around the corners of objects and interfere constructively and destructively when they are superimposed. They also transfer energy continuously to the areas where it is spread. In contrast, particles do not interfere nor diffract, but rather travel in straight lines and collide with other objects, transferring energy in a single localized point in space and time. These interactions obey the laws of conservation of energy and momentum. However, if the wavelength of a light source is made very small, the diffraction effects can be neglected, and the interference fringes are so closely spaced that they are practically unseen. This means that the stream of waves can be indistinctly interpreted as a beam of light waves or photons. Considering this last idea, wave-particle duality seems a little more plausible.

Despite Einstein's radical new idea, many physicists remained sceptical at first. In particular, Max Planck was one of such physicists that perceived Einstein's idea as inconceivable. In his view, light quanta could only be located in the processes of absorption and emission, and for the rest, light behaved as a wave.

Despite clear opposition by some, the idea of wave-particle duality was also accepted by a few physicists who were willing to accept new ideas. One of these physicists who was impressed by Einstein's ideas was Louis de Broglie (1892-1987), who went on to make the next biggest contribution to the field of quantum physics. In 1924, de Broglie presented his doctoral dissertation, where he introduced a highly speculative yet logical idea. By accepting Einstein's wave-particle duality, he thought that if light could behave as a wave and as a particle, perhaps all other known particles, such as electrons and protons, could also behave in such way. As these subatomic components were already thought to behave like particles, the difficulty in his proposition lay in creating a wave model for matter. To do so, he used Planck's equation, the classical expression for energy and momentum of an electromagnetic wave ($E = pc$), and the relationship between frequency and wavelength ($\nu = c/\lambda$). Substituting the two last expressions into the first and rearranging terms, de Broglie found the wavelength of a matter wave to be

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

Where λ is the wavelength, h is Planck's constant (with a value of $h = 6.626 \times 10^{-34}$ J·s) and p is the single particle's momentum. Similarly, he thought, the frequency can be obtained simply by rearranging Planck's equation into

$$\nu = \frac{E}{h}$$

Where E is the energy and ν is the frequency. This new idea for matter would theoretically apply to all sorts of objects: from the smallest particle to a football, for example. Despite this, experimentally proving macroscopic objects could theoretically behave like waves is practically impossible, as the first equation suggests that massive objects have minuscule wavelengths. Very small wavelengths, as explained before, entail negligible diffraction and interference effects, thus making wave and particle effects indistinguishable and interchangeable.

Taking this into account, it is clear that an effective confirmation of the so-called de Broglie hypothesis could only be obtained by using subatomic particles. Indeed, two independent experiments were performed, both of which used electrons as their study subject. On the one hand, George Thomson (1892-1975) was able to obtain the diffraction pattern for electrons using a thin metallic foil. On the other hand, Clinton Davisson (1881-1958) and Lester Germer (1896-1971) discovered electron interference by accident while scattering an electron beam on a nickel surface at Bell Telephone Laboratories. Regardless of the experiment, the same conclusion was reached: electrons also exhibited wave-like properties.

After de Broglie's ideas were published, another layer of difficulty was added: the problem that had been puzzling scientists for centuries was also observed to affect other particles. Despite this, thanks to this discovery, wave-particle duality seemed more credible. The next stage of development in quantum physics therefore consisted in trying to understand in more detail how the wave and particle aspects of matter and light worked.

One of the first things that scientists looked into was the equation that described the wave-like propagation of light and matter. Given that the displacement for waves on a string is written as $y(x, t)$, physicists knew that the displacement of a light wave was equivalent to the electric and magnetic field. However, it was not known what the analogous property for displacement was in the case of matter waves. In 1926, Erwin Schrödinger (1887-1961) published a paper in which he was able to describe what the wave equation would look like for matter waves. However, he was not able to give a physical explanation for the displacement of a matter wave, a property he designated as $\Psi(x, t)$.

Further developments by Max Born (1882-1970) showed that although no significance could be linked to $\Psi(x, t)$, an interpretation could be given for its square value. From classical physics, it is known that the energy per unit volume of a wave is proportional to its displacement or amplitude squared. However, because in quantum physics energy is proportional to the number of quanta, it is equally valid to say that the displacement of a wave squared equals the number of quanta per unit volume. Therefore, given a situation where the amplitude of the wave varies along a screen (such as the interference fringes of the double slit experiment), the points of interference maxima will have a greater number of quanta than the interference minima, that will have none. Considering this, if a single quantum is made to pass through the slits and impact the screen, it is more probable that it will impact close to the interference maxima than the interference minima. In other words, the probability that a quantum impacts the screen at any point, depends on the amplitude of the wave at that given point. Mathematically speaking, in one dimension, allowing $P(x)$ to be the probability density of dx for electrons with a wave function $\Psi(x, t)$, we can write the probability density as

$$P(x)dx = |\Psi(x, t)|^2 dx$$

or simply

$$\boxed{P(x) = |\Psi(x, t)|^2}$$

Even though these equations describe the probabilities of finding an electron (or just about any other particle), similar expressions can be found for light, as it behaves in the same way. Nonetheless, Born's interpretation of the amplitude squared entailed that light and matter quanta do not follow a determined path according to certain internal unknown properties, as was previously thought. As Born himself stated about the probabilistic nature of quanta:

> This raises the whole problem of determinism. From the standpoint of our quantum mechanics, there is no quantity that could establish the effect of a collision causally in the individual cases; however, up to now, we have no clue regarding the fact that there are internal properties of the atom that require a definite collision effect, even from experiments. Should we hope to discover such properties (perhaps phases of the internal atomic motions) and to determine the individual cases? Or should we believe that the agreement between theory and experiment regarding our inability to give conditions for the causal

> evolution is in pre-stabilized harmony with the fact that such conditions do not exist? I myself tend to abandon determinism in the atomic world (Born, 1926: p.3)

Despite his indeterministic point of view, his ideas were contradicted by many physicists working on quantum mechanics, such as Schrödinger and Einstein. In particular, the latter was in such disagreement that he wrote a letter to Born to express his opinion. It is this letter that contains the famous paraphrased expression "God does not play dice":

> Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing. The theory says a lot, but does not really bring us any closer to the secret of the "Old One." I, at any rate, am convinced that He is not playing at dice (Einstein, 1926).

Although disliked by some, after Born's probabilistic theory was published, quantum mechanics became ever more indeterministic. Only a year later, one of the most important principles about the nature of the small was published by Werner Heisenberg (1901-1976).

To study and understand the behaviour of photons and single particles, it is sometimes quite useful to make a model on their predicted aspect. In the case of light, because of wave-particle duality, the model must incorporate both wave and particle-like features. As a result, one of the most useful visualizations is the wave packet, a wave that is localized in space and time. Although still too classical, wave packets can diffract and interfere because of their undulations, while being able to impact at a point of a screen because they are localized. The creation of such bundles of waves is a result of the superposition of many harmonic waves of very similar frequencies. The more harmonic waves of slightly different wavelengths are considered, the more localized the wave packet will be.

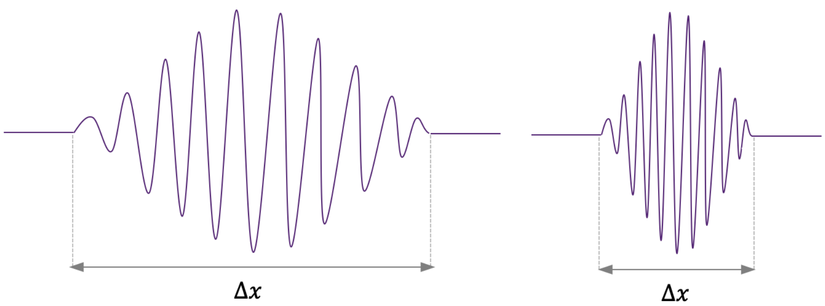

Figure 18 Two wave packets, the right one is more localized than the left one. Own work.

Keeping the idea of a wave packet in mind, Heisenberg realized that there are uncertainties in the measurements one can make of a certain pair of properties in a photon or single particle.

For instance, there is an uncertainty between the position and momentum. This means that precisely measuring the position of a particle causes its momentum to be measured with great inaccuracy, and vice versa. To better illustrate this idea, we have to consider a wave packet. Even though wave packets are localized, they cannot be pinpointed to an exact location, they are spread over a determined space. However, as stated before, if we wish to make the wave packet's localization as accurate as possible, more harmonic waves of nearly identical frequencies have to be superimposed. Therefore, if an accurate measurement of the position is made, more frequencies, and thus wavelengths, are going to be needed. The problem is that the momentum of a photon or any other particle is known based on its frequency (as expressed by the relation between wavelength and momentum $p = h/\lambda$). Hence, if the position is precisely measured, there will be more frequencies and thus an imprecise measure of momentum. Conversely, if the wave is spread (imprecise location), fewer frequencies will be superimposed and the momentum will be more defined.

Mathematically speaking, Heisenberg's uncertainty principle states that the product of the standard deviation of position and momentum (i.e. the measure of the uncertainty), Δx and Δp respectively, is always greater than or equal to $\hbar/2$, where $\hbar$ is the reduced Planck's constant ($\hbar = h/2\pi$). The uncertainty principle can be expressed as

$$\Delta x \Delta p \geq \frac{1}{2}\hbar$$

Similarly, an uncertainty relation can be established between energy and time. Despite being strange at first, these uncertainties served as the base for Niels Bohr's (1885-1962) ideas on wave-particle duality and the nature of the very small.

Although the idea of wave-particle duality had been accepted for a few years, it was not clearly known how it could work. All that was known was that in situations of emission and absorption the model of quanta was preferred, whereas for situations involving propagation the wave-like behaviour was dominant. Therefore, since one or the other model was more fitting depending on the situation, it was hypothesized that perhaps both models are needed. In 1928, and following Heisenberg's uncertainty principle, Bohr explained how both models could work together to explain light and matter. Heisenberg realized that the more accurately the position of a particle is known, the more imprecise the momentum becomes. The same can be said for energy and time, so that $\Delta x \Delta p = \Delta t \Delta E$ in the above equation. From here, Bohr thought that perhaps the uncertainty meant that the space-time variables are mutually exclusive from the energy-momentum variables. In other words, a choice had to be made between the description of one or the other sets of variables. This idea reminded Bohr of wave-particle duality and the equations that describe it: the Planck relation ($E = hv$) and de Broglie's wavelength-momentum expression ($\lambda = h/p$). These equations, he thought, contain energy and momentum variables, which are associated with particles, and frequency and wavelength variables, which are wave-like characteristics. Therefore, Bohr inferred that the wave and particle behaviours followed a similar exclusion as the position and momentum in the uncertainty principle. Light and matter were both a wave and a particle, but these two behaviours are exclusive: when it is accurately described as a wave, it is inaccurately perceived as a particle and vice versa. The idea that light and matter exhibits both behaviours but never simultaneously is what Bohr called the complementarity principle.

As light and matter are seen to behave as discrete particles during interaction processes, Bohr realized that one of the main implications of his theory was that the simple act of observation (a type of interaction) could alter the state of a quantum object. As he explained himself:

> As emphasised by Einstein, every observation or measurement ultimately rests on the coincidence of two independent events at the same space-time point. Just these coincidences will not be affected by any differences which the space-time co-ordination of different observers otherwise may exhibit. Now the quantum postulate implies that any observation of atomic phenomena will involve an interaction with the agency of observation not to be neglected. Accordingly, an independent reality in the ordinary physical sense can neither be ascribed to the phenomena nor to the agencies of observation (Bohr, 1928: p. 1).

Overall, the ideas exposed by Born, Heisenberg and Bohr can be grouped into the Copenhagen interpretation, a collection of views that aims to offer an explanation on the behaviour of light and matter. Following the ideas developed by these physicists, the Copenhagen interpretation states ideas such as that quantum nature is indeterministic or that the act of observation has implications upon the quantum system. Although heavily criticized by physicists such as Einstein, the Copenhagen interpretation is still to this day one of the most accepted interpretation of quantum mechanics.

4.2 Another take on the double slit experiment

After the publication of the main concepts of quantum mechanics, the question regarding the nature of light was seen from another point of view. Now, both light and matter were seen to behave as both a wave and a particle, as defined by Bohr's complementarity principle. These small units could also be described by Schrödinger's equation and were highly indeterministic. However, how does the new quantum theory adapt to my experimental data? More specifically, how is it able to explain the wave-like interference fringes? In this section, I will look into the quantum-mechanical interpretation of the double slit experiment.[11]

First of all, I will consider the idea that during the propagation of light the wave-like aspect is dominant and that during emission and absorption processes, particle-like behaviours are preferred. In the double slit experiment, a light beam is split by two closely spaced slits and the interference pattern that results is seen on a screen. This means that from the time the beam of light leaves the laser until it impacts the screen, and while passing through the slits, it behaves more like a wave. However, once the beam of light impacts the screen, and thus interacts with its particles, the wave-like nature suddenly changes into the discrete packets of energy we know as quanta. This immediate change of behaviour is what is sometimes referred to as the wave function collapse because all possible outcomes of the wave function are reduced to one upon interaction.[12]

A similar case can be described in the photoelectric effect. From the time the light leaves the lamp until it reaches the cathode in the photoelectric cell, the wave theory of light is predominant. However, the absorption and transmission of energy from the photon to the electron has to be modelled using the corpuscular nature. Given that the electron is excited after the interaction with the photon, it leaves the cathode and travels through the photoelectric cell as a wave until it reaches the anode.

[11] It is important to note that both the double slit experiment and the photoelectric effect can be analysed considering the theories mentioned above. However, due to the fact that the photoelectric effect consists in a rather simple energy exchange between a photon and an electron, I believe it is more interesting to look into the double slit experiment. It should also be considered that the double slit experiment provides a clearer example and application for most of the quantum theories in the last section.
[12] It is important to keep in mind that although I performed this experiment using laser light, all the ideas in this section can be applied to any other particle.

Returning to the double slit experiment, the idea that light travels preferably as a wave would explain why we observe an interference and diffraction pattern, and why the mathematics behind it are based on waves. Despite this, it would be reasonable to argue that even though we can imagine how the wave-like propagation could take place, we do not see the individual point-like photons on the screen, but rather a faded light and dark pattern. Although a valid argument, the reason we do not observe the individual collisions is because a light beam is usually made up of hundreds of thousands of light quanta and, therefore, the individual spots are practically imperceptible.

As further proof, we can actually measure how many photons per second impact the screen. From Planck's relation, we know that $E = nh\nu$, and thus that the number of quanta is given by

$$n = \frac{E}{h\nu}$$

or

$$\boxed{n = \frac{E\lambda}{hc}}$$

If we substitute the energy for the power of the laser, we will obtain the number of light quanta in a second. Knowing that the maximum power of the laser I used for the double slit is 30 ±1 mW, and that the wavelength of light is λ = 632.8 ±0.1 nm, we know that the number of photons per second equals

$$\boxed{n = (9.6 \pm 0.3) \times 10^{16} \text{ photons per second}}$$

Hence, it is clear that the individual quanta cannot be seen. However, if the light intensity is made sufficiently small, and a specialized photon detector camera is used, the individual spots can actually be distinguished. This has actually been done many times, and the outcome has been photographed.

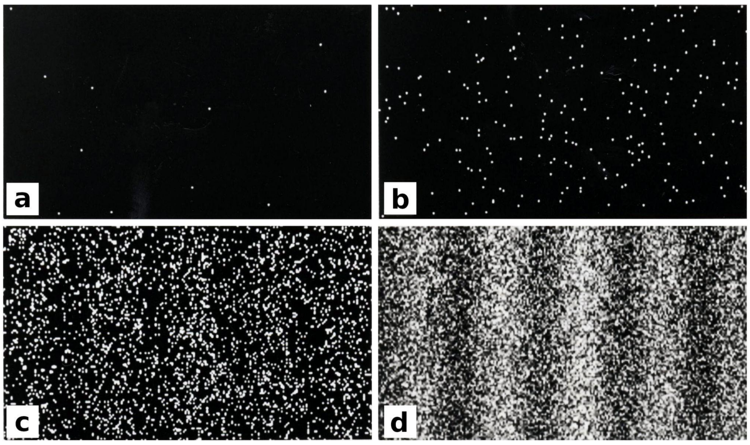

Figure 19 Results of a double-slit-experiment performed by Dr. Tanamura showing the build-up of an interference pattern of single electrons[13]. Numbers of electrons are 11 (a), 200 (b), 6000 (c), 140000 (d). Author, Dr. Tanamura. *Wikimedia Commons*. CC licence. Extracted from <https://commons.wikimedia.org/wiki/File:Double-slit_experiment_results_Tanamura_4.jpg>

Therefore, it is clear that the idea that light travels as a wave and departs as a particle adjusts perfectly to my data for the double slit experiment. Despite this, we can further look into the experimental data by analysing the interference pattern. As I calculated in my experiments, the spots for interference maxima and minima are given by

$$d\sin\theta_m = m\lambda$$

and

$$d\sin\theta_m = (m - \frac{1}{2})\lambda$$

respectively. However, from a photon point of view, and as seen in the last picture, these points actually correspond to the spots where most and least photons can be found in the pattern. In other words, these formulae allow you to calculate the points where the maximum and minimum probabilities of finding a photon are. The most likely place for a photon to impact is $d\sin\theta_m = m\lambda$, whereas no photons will ever impact in $d\sin\theta_m = (m - \frac{1}{2})\lambda$. From the calculations for the interference pattern, I was able to find that the points with the highest probabilities of finding a photon are y_1 = 4.87 ±0.02 mm, y_2 = 9.74 ±0.05 mm and y_3 = 14.61 ±0.07 mm from the central maximum. Similarly, the first spot of zero probability for the single slit pattern is found at y_1 = 15±2 mm from the central maximum.

[13] The picture represents the build-up of electrons, but this pattern is the same for photons and other single particles.

These points for the interference maxima and minima can also be thought of as the points where the light wave's amplitude is at its peak and lowest value. These points obviously correspond to the brightest and darkest points, or in other words, the points of maximum and zero light intensity. From classical physics, we know that the intensity of a light wave is proportional to the square of the amplitude so that $I \propto A^2$. However, because the intensity is the energy per unit area per unit time, it can be thought of as the probability of finding a photon per unit area per unit time. Correspondingly, the amplitude of a light wave is linked to the electromagnetic field.

Taking this into consideration, we can reinterpret the intensity graph I made for the interference fringes of the double slit as representative of the light wave's amplitude squared at all points. Going one step further, the graph is also an indicator of the number of photons that would impact each point of the screen or, as otherwise thought, the probability of finding a photon.

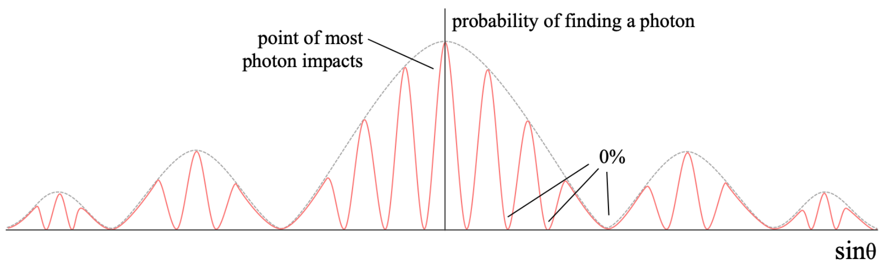

Figure 20 Probability of finding a photon as a function of angle. Own work.

To summarize all the ideas stated in this section, I will describe the full path followed by a photon in the double slit experiment, from the time it leaves the laser until it impacts the screen. First, I will start by considering that the light intensity is reduced to a very low level. Under this condition, only one photon at a time is present in the system and therefore cannot come into contact with other photons. The journey starts when the photon leaves the laser, and it begins to propagate forward as a wave. The interesting part occurs when the light reaches the slits: if it were a classical particle, you would expect the photon to pass through one of the two slits. However, because light travels in a wave-like manner, the single photon actually passes through both slits and interferes with itself (this interference pattern is the same one we observe after many photons have impacted the screen). As we know, this pattern not only describes the intensity of light, but also the probabilities of finding a photon.

Therefore, the photon then continues to travel in a wave-like manner until it reaches the screen. At this point, due to interaction, the wave function collapse occurs and then based on the probabilities described by the interferences, the photons appear in a single spot as a single unit of energy, as if no wave had ever existed. Once the first photon reaches the screen and this process starts to repeat itself over time, the photons fill up the screen and eventually the interference pattern can be seen.

Although apparently counterintuitive and strange, this new view of light offered a solution to the conundrum that scientists had faced at the beginning of the 20th century. The new quantum theories adapt and explain quite nicely the double slit experiment in terms of wave-particle duality and probabilities of finding a photon. However, this view of light and the quantum reality is somewhat ambiguous and difficult to imagine. Why would light and matter undergo such difficult processes? There are many unanswered questions, and the nature of light and matter is still a source of debate today.

4.3 Other models for the nature of light and matter

Despite the advancements in our understanding of light and matter, there is still no complete explanation for their nature and behaviour. According to the Copenhagen interpretation, photons and other particles are sometimes more like waves and on other occasions they are more similar to particles. However, to many physicists, this idea is still too abstract and incomplete to be regarded as true. One of the main critics of the Copenhagen interpretation, Albert Einstein, wrote about the quantum theories:

> This double nature of radiation (and of material corpuscles) is a major property of reality, which has been interpreted by quantum-mechanics in an ingenious and amazingly successful fashion. This interpretation, which is looked upon as essentially final by almost all contemporary physicists, appears to me as only a temporary way out (Einstein, 1949: p. 51);

As a consequence, over the following years, many interpretations that aimed to explain light and matter were created. In this section I do not wish to look into the interpretations, but rather the new models and ways to visualize light and matter considering their wave and particle-like behaviours. Furthermore, I will also consider how well they adapt to the double slit experiment, just as I did for the ideas of the Copenhagen interpretation.

4.3.1 Dismissing particles: Quantum field theory

Ever since Newton published his mechanical views in *Principia*, the world was seen in terms of point-like particles moving through space. Although revolutionary, his ideas do not apply as efficiently when considering microscopic phenomenon. For instance, particles are useful analogies when analysing absorption and emission processes, but they are not able to explain the propagation of light and matter. Therefore, particles are not an ideal model to describe atomic behaviour, and are sometimes labelled as too classical.

A different approach to the problem that has been partly disregarded was proposed by Faraday more than a century later. If you recall, in section 2.3 we talked about Maxwell's and Faraday's contributions to the nature of light. It is in this point where we specified that Faraday imagined light as "a high species of vibration in the lines of force which are known to connect particles and also masses of matter together (Faraday, 1846: p. 451)". In other words, Faraday visualized light as a vibration in a force field that permeates all space, rather than a wave travelling through the aether like his contemporaries. His idea later helped to pave the way for Maxwell's equations and the notion of an electromagnetic field. Despite this, the idea of the aether was still prevalent at the time, and it was not dismissed until the results from the Michelson-Morley experiment were published.

At the beginning of the 20th century, the idea of fields started to resurface again. After disproving the aether, it was once again thought that, perhaps, no medium was needed for the propagation of light. Fields were a condition of space itself, and light was simply its vibrations. This was the start of quantum field theory.

After the main postulates of quantum mechanics were published, wave-particle duality became the standard way of visualizing light and matter. However, as we have seen, this model is still unable to fully explain the observed behaviour. As a result, some physicists hypothesized that perhaps we should not be looking into wave-particle duality, but rather wave-field duality. Particles, after all, are one of the few classical concepts that still remain inside this modern framework. They just do not fit in.

Quantum field theory (or QFT for short) considers light and matter as unbounded fields, where quanta represent small disturbances emerging from them. The equations that describe the fields for light and particles are actually known, and they are Maxwell's equations and Schrödinger's equation respectively. This new theory also incorporates quantum mechanical postulates, which means that the fields have to be quantized, and special relativity.[14]

Under these premisses, photons, electrons, protons, and so on, are seen as excitations of the field, because they incorporate additional energy to it as multiples of $h\nu$. These quanta represent the superposition of different frequencies, which makes them localizable in a sense, but not precisely pinpointed to a place in space. This adapts to Heisenberg's uncertainty principle. Other important characteristics of these quanta are that they are created and destroyed at once due to their quantized nature, and that they carry energy and momentum that allows them to behave like a classical particle upon interaction.

Now that I have explained the basic structure and properties of this model, we will further analyse QFT by considering the double slit experiment. How do fields and disturbances in the field explain an interference pattern? Knowing that performing the experiment one quantum at a time does not alter the outcome (i.e. the interference pattern is unchanged whether one or multiple quanta pass the slits at the same time), must mean that each quantum possesses the information of the entire pattern. Considering this, we can logically conclude that the quantum must be spread through the whole pattern. This is easy to visualize if we consider a quantum to be a vibration in a field. The vibration crosses both slits and interferes with itself to create a pattern. The difficulty with this model arises from explaining the particle-like behaviour seen in absorption and emission. If the localized disturbance is said to carry energy and momentum, we might infer how the interaction could seem like that of a set of particles. However, how could vibrations explain the spots registered in the photodetector cameras? Art Hobson, the author of a paper on particles and QFT, points out why we should not rely on these images. Each flash in the images, he explains, represents the interaction of a quantum with the screen. The quantum interacts and the monitor registers it as a point. This, however, just means that the quantum can interact locally with the screen, but not necessarily that it is like a classical particle. We must forget about the particle idea and visualize the phenomenon as the excitation of a field that, upon interaction, acts on a small (but still spread out) area of energy $h\nu$. As stated by Hobson, "Localization is characteristic of the detection process, not the quantum that is being detected (Hobson, 2012: p. 14)".

[14] Keeping in mind that Schrödinger's equation is a non-relativistic expression, a modified version of it had to be found. The new equation that accounted for special relativity was formulated by Paul Dirac (1902-1984).

In short, quantum field theory explains that we should not bother with waves and particles, as fields are all there is. It is one of the few theories that dares to dismiss Newtonian particles and explain nature in terms of fields, a rather modern view supported by scientists such as Faraday and Einstein. Although it might be hard to grasp at first, QFT provides one of the most unique and plausible explanations for the ambiguous nature of light and matter.

4.3.2 The de Broglie-Bohm theory and the walking droplets experiment

Another model worth looking into is that developed by Louis de Broglie in 1927 and then rediscovered by David Bohm (1917-1992) in 1954. Known as the de Broglie-Bohm theory, this theory proposes that both particles and waves are necessary elements to describe atomic phenomena. The main idea in their theory is that light and matter are made up of particles that are guided by a wave equation, forming together a deterministic system. In other words, the wave equation, which in this theory takes on the leading role, determines the position of the particle at all times, and thus guides it through space. Because of this, the de Broglie-Bohm theory is sometimes also referred to as the pilot-wave model.

A useful analogy to understand this concept is a water droplet that, instead of merging into a body of water, repeatedly bounces on its surface. The continuous motion of the droplet on the water creates a series of waves that then influence the droplet's movement under the right circumstances. This practical way of visualizing the de Broglie-Bohm theory has actually been used before to test how well this model adapts to various phenomena observed in light and matter, and the results are striking.

In 2010, a group of four scientists in France performed an experiment where they tested the de Broglie-Bohm analogy using, as they called them, walking droplets. In order to do so, they used a small cell containing a silicon oil that is more viscous than water, where small droplets were placed and made to bounce. However, as we all know, if a liquid droplet falls into a surface with the same liquid, it will merge with it, not bounce. To prevent the droplet from incorporating into the body of the liquid, the group made the cell vibrate vertically with an acceleration greater than gravity. Under these conditions, the droplet remained separate from the surface and continuously bounced on top of the liquid body. Furthermore, as a result of this constant interaction, a series of spherical waves propagating outward were created from the droplet.

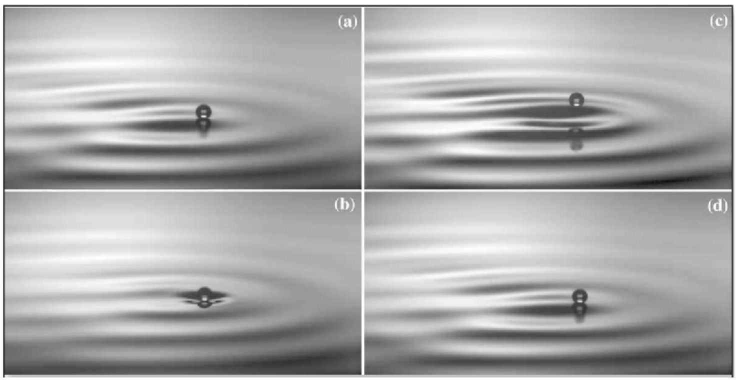

Figure 21 Four successive pictures of a walker, side view. Authors, Y. Couder, A. Boudaoud, S. Protière, E. Fort. Extracted from <https://www.europhysicsnews.org/articles/epn/pdf/2010/01/epn20101p14.pdf>

The group also explained that although the waves created were usually quite attenuated, if their amplitude was increased enough, the droplet would start to move horizontally. This effect is due to the fact that liquid surfaces become unstable when subject to vertical oscillations higher than a threshold value. The result from this instability is an asymmetrical wave-perturbed surface that causes the droplet to move horizontally besides the vertical oscillations. The moving system formed by the droplet and the associated waves was then named "the walker" and further studied by the group.

One of the first important remarks the group made was that this analogue model of light and matter predicted that both wave and particle aspects are present and necessary. If the droplet keeps bouncing, both behaviours are seen, but if the droplet suddenly merges into the surface, both the wave and the particle elements disappear. This is a new way of approaching the problem of the nature of light and matter.

Further investigations of the walker were focused on how they behave during reflection from a wall and interaction with other walkers. However, their most significant finding was when they looked into the diffraction and interference of single walkers. To study these properties, the group modified the cell by incorporating a bar of metal to its bottom. Although the bar was sunk into the liquid, its purpose was not to rise to the surface, but rather to reduce the thickness of the liquid layer at a given point. This reduction in thickness would essentially act as a wall for the walker, and thus only allow it to cross through an opening in the middle of the bar. This set-up, analogous to the double slit filter used in Young's experiment, would allow the diffraction and interference effects of the walker to be observed when it crossed the narrow opening.

Once the experiment was conducted many times, the group realized some deviation angles were more frequent than others. Looking deeper into this, they made a histogram for the number of walkers N that deviated for each angle α. After 125 continuous crossings, they obtained the following graph.

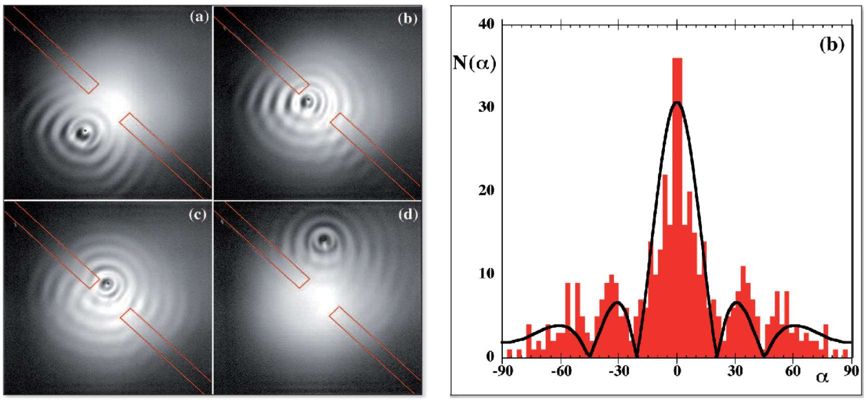

Figure 22 Four successive pictures, a to d, of a walker moving through a slit (left). Histogram of measured deviations for N=125 successive crossings of single walkers through a slit (right). Authors, Y. Couder, A. Boudaoud, S. Protière, E. Fort. Extracted from <https://www.europhysicsnews.org/articles/epn/pdf/2010/01/epn20101p14.pdf>

The similarities with the interference pattern for the double slit experiment are striking. Moreover, they also noted that if this experiment had been done using a double slit, the droplet would have crossed one of the two slits while the associated waves would have crossed both. As a result, the interference of the waves coming out of the two slits would have guided the droplet towards a certain angle. These angles, just as the graph above, would have been the same as those in the double slit pattern for light.

Although many similarities between the observed behaviour of light and matter and the walking droplets can be traced, the group of scientists also pointed out there are a few notable differences. Some of these include the fact that the experiment is performed with macroscopic walkers, and thus that Planck's constant is inappreciable; the high dissipation of this system in comparison to the non-dissipative quantum system, the material medium used for the walkers, or the fact that measurements on the walkers do not alter their behaviours.

Despite the similarities and differences, this experiment and de Broglie-Bohm theory surely gives us a useful insight into alternative ways to visualize and understand light and matter.

4.3.3 The cordus conjecture

In 2012, another research group, this time from New Zealand, approached the problem of the nature of light and matter by investigating and assessing potential new models. After conducting the double slit experiment and considering the observed evidence, they began to develop several hypothetical models for light. These designs and ideas were then selected according to how well they met certain physical criteria, such as reflection and refraction. Finally, after some refining and reevaluating, the group created a conceptual model called the cordus.

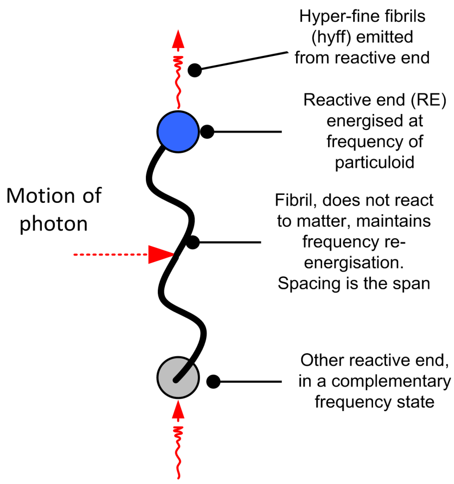

Figure 23 Cordus model of the photon. Author, John Pons. *Wikipedia Commons*. CC licence. Extracted from <https://en.wikipedia.org/wiki/File:CordusConjecture2.21_PhotonCordus.png>

The idea behind the cordus is that all units of light and matter (e.g. photons, electrons, and neutrons) contain an internal structure called "cordus". This structure consists of two reactive ends that act like a particle, connected by a small fibril that does not interact with other matter. The reactive ends are energized at a frequency and emit force pulses along a line called hyperfine fibril. Further research into this bipolar structure revealed how it could explain properties such as the double slit experiment, reflection and refraction.

As done in the last section, I will look into the explanation the cordus gives for the double slit experiment. According to the group who developed the cordus, if this structure was made to cross the double slit, it would go through both: one reactive end through each slit. The fibril that connects both ends would then pass through the slit space unnoticed because it does not react with matter. As the reactive ends pass through the slits, since they emit force pulses from the hyperfine fibril, they would interact with the material surface of the slits and thus bend its trajectory by a certain angular amount. The result from this interaction would be the interference fringes, where the number of photons, or in this case cordus, change according to the angle displaced. Once the cordus has reached the screen, the location of the energy bundle is determined by the first reactive end to interact with the screen, a process which is said to be random. When one of the two ends has interacted, the other end and the fibril collapse and disappear, thus seeming as if only one spot ever existed.

This process can then be repeated many times to obtain the known interference fringes. It is important to note that this process is said to apply to all light and matter "particles", whether they are made to pass the slit one by one or not.

The cordus conjecture is yet another model that offers an alternative and deterministic view of light and matter. It is able to explain the double slit in terms of force interactions with the slits, instead of relying on constructive and destructive interference, and it considers the wave and particle aspects as two different outputs of the same system. However, the authors of the paper themselves remark that the cordus conjecture is no more than a simple conceptual idea, and that much work still remains to be done, especially on the mathematical side.

5. Conclusions

The nature of light is complex. I began this journey simply trying to understand what light was, and in the process got caught up trying to uncover the fundamental structures of reality. Due to the highly speculative nature of this subject, I will organize my findings by reconsidering the initial possibilities and verifying or disproving them. It must be reminded that the question I attempted to answer in this project is: based on the known theories of light, which model best describes its nature and behaviour?

1. The particle model. Light as a particle.

The particle theory was the first attempt to understand light. It is able to explain reflection and refraction, the latter with a few difficulties. Most importantly, this model allows physicists to make sense of phenomena such as blackbody radiation, the photoelectric effect or the Compton effect. However, particles are unable to explain the diffraction and interference observed in the double slit experiment or the Arago spot. Hence, the classical particle model is generally unfit to explain light. We cannot consider light as solely a particle.

2. The wave model. Light as a wave.

Together with the particle model, the wave model constitutes the classical views on light. Waves help to explain reflection, refraction, diffraction and interference. Despite this, because waves are classically opposite to particles, they do not offer an answer to emission and absorption processes. Therefore, although it explains a wider range of phenomena, the wave theory is unsatisfactory in fully explaining the observed behaviour of light. Light cannot be simply modelled as a classical wave.

3. The wave-particle duality model. Light as both a wave and a particle.

Given that light exhibited both wave and particle behaviours depending on the scenario, physicists thought that perhaps light should be considered as both. In this project, I have analysed three different theories that contemplate this possibility.

First of all, I talked about the basic postulates of quantum mechanics and I introduced one of the earliest theories: the Copenhagen interpretation. By incorporating the ideas of physicists such as Born, Heisenberg or Bohr, the Copenhagen interpretation has been able to perfectly adapt to the observed behaviour of the double slit experiment. It has also been able to solve the particles versus waves problem by assuming both models are needed and dominant depending on the situation. However, some physicists have regarded this theory as incomplete, and, additionally, it raises questions about determinism and indeterminism in the quantum scale.

Secondly, I looked into another model that considers waves and particles, but this time, as simultaneous behaviours that influence one another. This theory is the de Broglie-Bohm theory. Although it approaches the problem from another perspective, the experimentation has been conducted using an analogous macroscopic system. This means that the satisfactory results obtained might not apply to atomic phenomena as efficiently. Light may not behave alike.

Thirdly, I considered the cordus conjecture. Even though it is probably the most unique model I have analysed, the authors of the paper themselves stated it is no more than a thought-experiment. It provides the basic ideas, but does not offer an exhaustive explanation of its inner workings and still lacks mathematical support.

Overall, the theories that consider both wave and particle behaviours provide a more accurate answer to the observed behaviour of light. However, each of the three theories fails to fully explain all of the aspects requiring consideration. Whether these doubts will be resolved or not in the future, I cannot tell. Therefore, I cannot objectively confirm nor deny that these theories are accurate models for light. It comes down to opinion and preference.

4. Another model. Light as neither a wave nor a particle.

In this paper, I have also talked about one theory of light that does not involve waves nor particles: Quantum field theory. This other approach considers particles to be too classical, and that light is instead a quantized field containing small disturbances. QFT is able to explain all observed phenomena, including the particle-like collisions. It takes the quantum ideas and observations, and it interprets them differently (e.g. Schrödinger's equation is seen as a field equation). Despite this, similarly to wave-particle duality models, it is not settled, and much research still needs to be conducted. Therefore, I cannot objectively provide an answer for this one either.

All in all, we can conclude that possibilities 1 and 2 can be disproved, but that 3 and 4 cannot be confirmed nor denied.

So, what is light? In the introduction of this project, I hypothesized that light must contain both the wave and the particle models within it simultaneously, and that this follows wave-particle duality. However, after looking into the problem, I would say that I cannot deny this possibility, but that I do not agree with it in some respects. My initial hypothesis was heavily influenced by the ideas of the Copenhagen interpretation and the early theories of quantum mechanics. However, although it is one of the most accepted models, there are still many unsolved questions that I cannot overlook.

Now, the most accurate and objective answer I can give to my initial question is that, to this day, there is simply no perfect or best model to describe light.[15] Light is still a mystery and the only thing that we know for sure is that it cannot be just a wave or just a particle. The nature underlying this phenomenon possesses characteristics similar to these two classical models. Both wave and particle behaviours are necessary to understand light, but we do not yet definitely know whether its nature is a combination of both or a radically different model that can be camouflaged as sometimes wave-like and sometimes particle-like. Nonetheless, I am sure that further research will be focused on possibilities 3 and 4. Until a solution is reached, the journey to understand light will continue.

However, just because there is no established answer does not mean that I cannot speculate. I believe that all this research has not only allowed me to come to the conclusion that there is no answer to my question, but also helped me to create an opinion as to what I believe light to be. To generate a worthwhile point of view, I have based my ideas upon the results of my experiments. Summarized, the conclusions from my double slit experiment can be stated as:

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[15] It must be noted that these statements also apply to all matter (e.g. electrons, protons, neutrons, etc). After the de Broglie hypotheses and the observation of electron diffraction, it was clear that, because electrons exhibited the same behaviours as light experimentally, they must fundamentally be alike. This means that the discussion that was once focused on light can actually be generalized into the nature of reality.

- Light does diffract and interfere, which must mean that it has a wave-like propagation and behaviour.
- The interference and intensity patterns match those of classical waves, and not particles. Multiple fringes are observed instead of two pronounced slits.
- The light source's wavelength (λ) and points of maximum and minimum intensities can be calculated using wave models and interference-based equations.

Similarly, the conclusions from my experience with the photoelectric effect can be stated as:

- Light is capable of providing enough energy to electrons, so they can leave the metal and create a current.
- The energy of the electrons freed, and thus the energy of the light source, is indeed proportional to its frequency.
- Planck's constant can be found experimentally, which must mean that it is a real physical constant.
- Because the energy is proportional to the frequency, and Planck's constant can be calculated, Planck's relation ($E = hv$), and thus quanta, must be a property of light and matter.

Based on these observations, it is clear to me that light (1) propagates similarly, if not, like a wave and (2) possesses quanta that can be detected during emission and absorption processes. Now, I must specify that I believe there is a difference between what we classically know as a particle and quanta. In this sense I agree with the ideas of QFT, because it seems to me illogical that despite all the differences between classical and quantum mechanics, we should still consider a Newtonian corpuscle. I prefer the notion that quanta may instead be an excitation in a field that can act like a classical particle. Or, if not an excitation in a field, some other model that upon interaction can be compared to classical particle collisions.

Another consideration that I believe is important to remark is that, similarly, the waves of light and matter are unlike classical waves. By definition, it is known that waves are a propagation that moves through spaces carrying energy. However, I have experimentally found that energy is indeed quantized. This must mean that, despite their resemblance with classical waves, light and matter waves are quantized. In other words, the energy they carry can only take certain discrete values. Nonetheless, this quantization does not affect the way that the waves propagates, as the interference pattern is the same in both cases.

You may have noticed that my opinion shares some similarities with the model proposed by QFT. This is because I think it is the best model we have to date to describe light and matter. Speaking of the other models, I have already mentioned that the wave-particle duality proposed by the Copenhagen interpretation seems incomplete to me. Although the ideas that it groups are extremely useful to understand quantum behaviour, I cannot fully come to terms with the fact that waves can "magically" or "instantaneously" turn into a particle when observed. I understand how it might work based on the idea of wave packets, but I am incapable of imagining how a sudden shift in behaviour might happen. The other two theories, the de Broglie-Bohm theory and the cordus conjecture, seem even more incomplete to me. The cordus is a model that incorporates both the classical wave and particle into one single unit. As I said before, I believe that light and matter waves and particles differ from classical waves and particles. Therefore, I dislike this model. The same goes with the de Broglie-Bohm theory. Additionally, I believe that if in the de Broglie-Bohm theory there really was a particle being guided by a wave, during emission and absorption processes we would be able to observe some kind of wave behaviour alongside the quantum. This does not seem to be the case.

Overall, I believe that we are currently in an interesting point in time with the problem of the nature of light and matter. Over the centuries, we have learnt a lot about this phenomenon, but we still have a long way to go. It has only been a little over a century since quantum mechanics was discovered, and still much research remains to be done to fully understand the microscopic world. So, until a definite conclusion can be reached, the debate over the nature of light will persist.

Personal conclusions and experience

When I started this project, I did not know what to expect. I knew about wave-particle duality and the fact that light presents a strange behaviour in the double slit experiment, but not much else. I thought that my answer would lean towards wave-particle duality, but now that I have understood the problem in detail, I believe that "no definite answer" is the most exciting answer that I could have reached.

However, this does not mean that I have not been able to achieve much in this project. In fact, it is quite the opposite. I have successfully attained all of my personal objectives:

1. I have understood all the ideas and theories behind light and its nature. This has probably been my favourite part of the project. Not only have I learnt about a variety of experiments and ways of approaching the problem, but I have also been able to understand the scientists' trains of thought and attitudes towards the problem thanks to quotations. I believe that the history of the research of light is one of the most interesting stories in the world of science.
2. All explanations have been justified either mathematically or experimentally. I have carried out two experiments that back up two ideas: the double slit experiment and the photoelectric effect. The rest have been justified mathematically as much as possible. However, It must be taken into account that not all theories have a mathematical basis, and that some others that do, exceed my current level of understanding, and are thus not included.
3. Lastly, in the theoretical conclusions above, I have provided my point of view on the nature of light. My opinion has been based on my personal observations with the experiments and several theoretical considerations.

Doing this project has taught me the importance of being organized and consistent with my work. I have learnt to select the important ideas and discard those interesting facts that do not contribute to the development of the main topic. However, more importantly, I have come to understand that sometimes I must be patient and allow myself to rest for a bit when I do not understand an idea or a formula.

All in all, this project has been a demanding, but nonetheless exciting journey. I have not only learnt about light and all of its complexity, but also about different ways of approaching this problem and of trying to find a solution. I am, overall, quite pleased with my work and the outcome of this project, and I hope it is well received.

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Annex

In the photoelectric effect experiment, six different filters are used. The wavelengths of these filters and the criteria used to choose them are indicated in the following graphs.

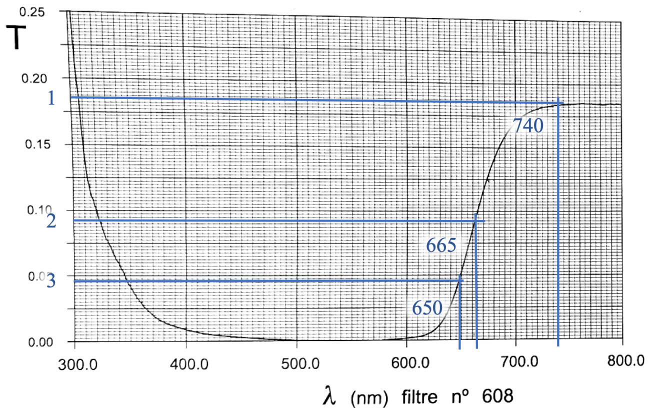

Figure 24 The three criteria marked on the graph for the red filter. Edited image from graphs provided by [Programa Argó advisor], UAB.

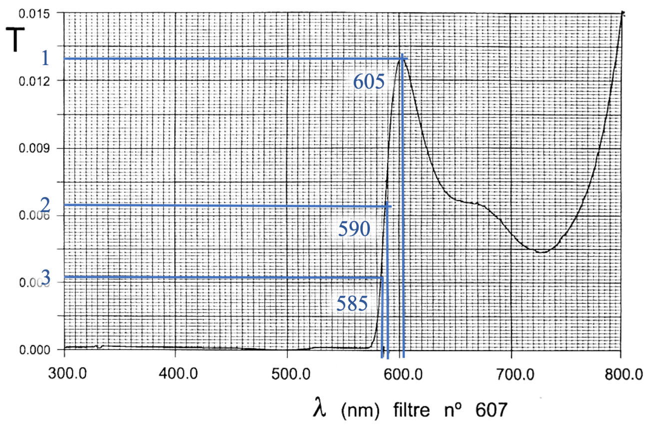

Figure 25 The three criteria marked on the graph for the orange filter. Edited image from graphs provided by [Programa Argó advisor], UAB.

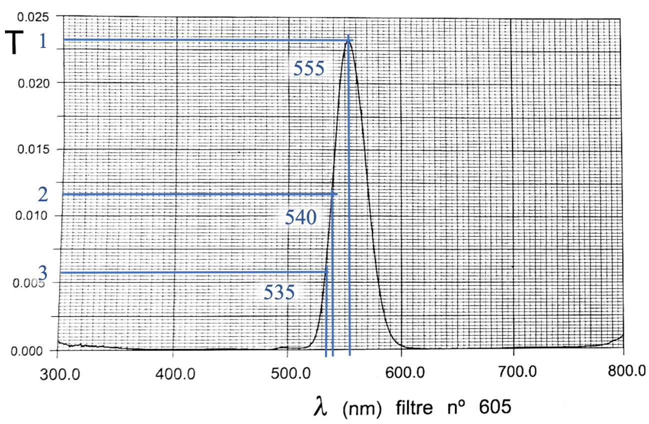

Figure 26 The three criteria marked on the graph for the yellow-green filter. Edited image from graphs provided by [Programa Argó advisor], UAB.

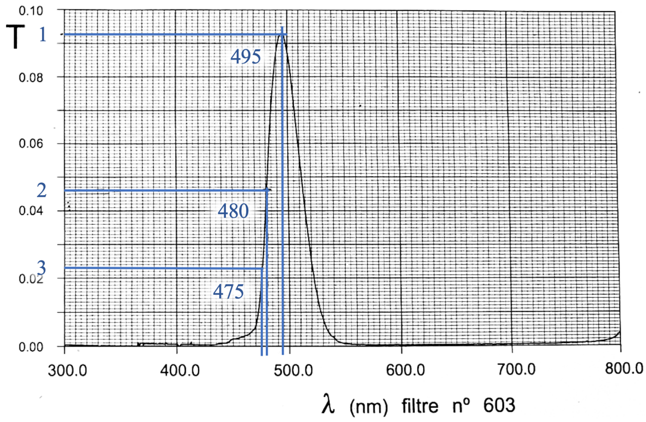

Figure 27 The three criteria marked on the graph for the blue-green filter. Edited image from graphs provided by [Programa Argó advisor], UAB.

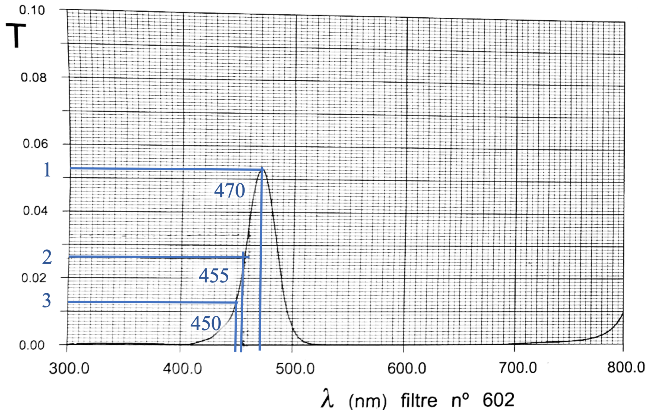

Figure 28 The three criteria marked on the graph for the blue filter. Edited image from graphs provided by [Programa Argó advisor], UAB.

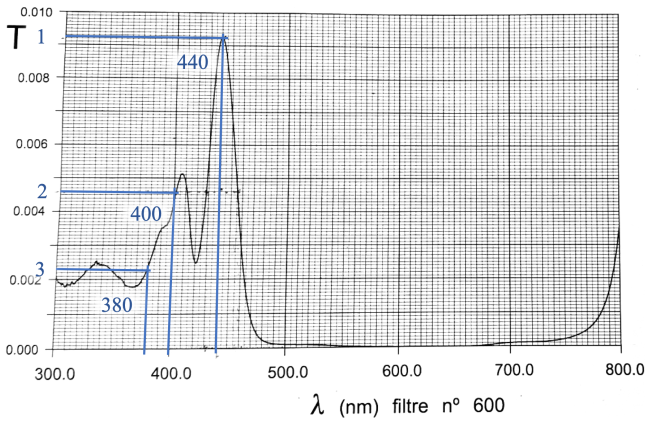

Figure 29 The three criteria marked on the graph for the violet filter. Edited image from graphs provided by [Programa Argó advisor], UAB.