A brief history of light

S. Rafi Ahmad*

Senior R&D Consultant, NEXTEK (UK) Ltd

In the beginning, God said, "Let there be light", and there was light—that's the origin of light, according to Genesis anyway. At the dawn of civilization our ancestors gazed at the ball of fire on the horizon and pondered about the wonders of the life-giving power of light emanating from this ball. Naturally the sun, the endless cosmic source of light, was elevated to the status of godhead. The Vedic and Egyptian scriptures and even the more modern religions, such as those of the Inca, testify to this status. However, for us, the mortals, light is still a 'thing' with which we see the world.

Our perception of the world is preconditioned by an acquired mental frame. We can only perceive forms or logical conclusions. If light is a 'thing' it must have a form; if it is an effect, there must be a cause associated with it. Enquiring minds continued the search for answers to the questions—what is the form of light or, what is its cause. The questions remained unanswered for millennia. Technology advanced far ahead of science. Man had been able to make light by burning wood, candles, gas and, later, by electricity. Man's ingenuity paved the way to an epoch-making technology for producing an amazing source of light called the laser.[1] But still, to this day, the quest for an understanding of the nature of light has eluded enquiring minds; light, as always, remains an enigma. The quest, however, has led us to a better understanding of the physical world and the interaction of light with itself and with the material world. The fact that our vision has everything to do with light begs the philosophical question—does matter exist because we see or feel it, or is light the essence of all matter? Indeed, as the philosopher Plato has proposed—is light indeed the shadow of God?[2]

Long before Aristotle another Greek philosopher, Empedocles, saw light as 'something' which travels through space at a finite speed. But Aristotle did not think light to be 'something', which travels. According to him, light is the actuality of what is known as 'transparency'. It is a property of the medium such as air, water, glass etc. that sets in motion the property of transparency in it and that motion extends up to and beyond our eyes. But light emanates from the sun and the stars and travels through the vast expanse of empty space. How can it be then a

* E-mail: sheikhrafiahmad@hotmail.com; website: https://sheikhrafiahmad.co.uk

1 Karl F. Renk, *Basics of Laser Physics*. Springer (2012).

2 Plato, *c*. 427–347 BC.

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property of the medium? To answer this question, the followers of Aristotle introduced the concept that the universe is not really empty at all, but filled with a phantom, undetectable and infinitely elastic matter called 'ether'. Light is therefore considered to be the manifestation of the property of this elusive ether. Aristotle's concept of light was completely abandoned after the Danish scientist, Ole Rømer, demonstrated in 1679 that light is indeed the cause of an effect, and that effect has a time lapse; i.e., the light is 'something' that travels with finite speed.[3]

The inquiry into that 'something' was first made on a scientific basis by the Dutch physicist Christiaan Huygens, in a small treatise on optics published in 1678. His vision of light was that it is a form of ripple emanating from every point in a source (Figure 1). The Swiss mathematician Leonhard Euler was the first to propose in 1768 that, just as the wavelength of sound waves determines their pitch, the wavelength of the light ripples determines the colour of that light. But the concept of light as a propagating ripple or some kind of wave did not stand up against the corpuscular theory of light propounded by the British scientist Isaac Newton (Figure 1).

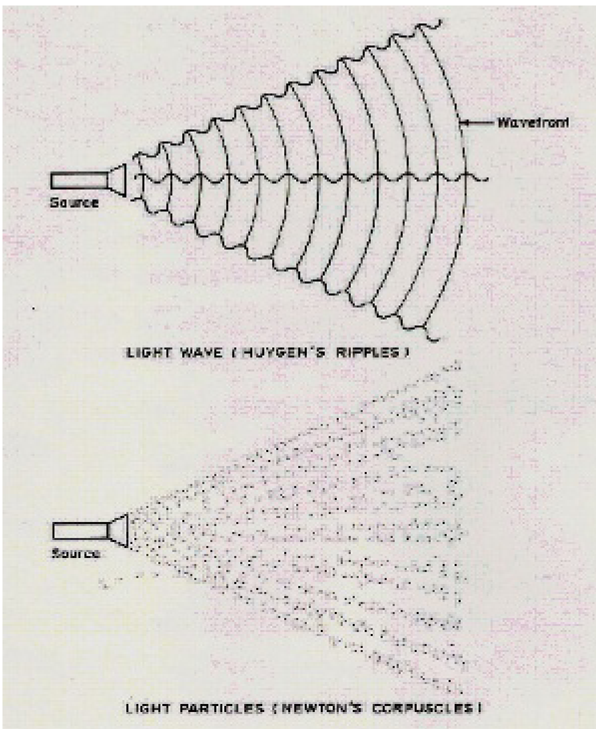

Figure 1. Visualization of Huygens's wave and Newton's corpuscular concepts of light.

[3] Mark Weston, *Finding the Speed of Light: The 1676 Discovery that Dazzled the World*. Thomaston, Maine: Tilbury House (2019).

Newton's concept of light as a stream of particles or 'corpuscles' having different colour properties[4] was not based upon any scientific experiments. He did not try to provide any explanation to many observed effects produced as a result of the interaction of light with matter. In response to some of the observed phenomena he simply made some conjectures. For example, the phenomenon of partial reflexion from glasses or water surfaces was interpreted in terms of the correct fit of the light corpuscles with the particles or voids of the condensed matter. The diffuse shadow of a sharp edge (diffraction pattern) was explained in terms of the wiggly motion of the corpuscles (like that of a snake or an eel). However woolly and seemingly unscientific Newton's interpretation of the interaction of light with matter was, his authority in the scientific world was so great that almost a century went by before enough experimental evidence was gathered to challenge Newton's corpuscular theory.

In 1801 a British medical doctor, Thomas Young, created a landmark in the scientific world by his famous 'light and two-slit' experiment. He observed that when light emanating from a slit (a point source) is allowed to pass through two slits and then on to a screen, a bright and dark pattern, called fringes, appears on a screen or is captured by a photographic plate in the place of the screen (Figure 2). Only spherical waves emerging from the two slits (S_1 and S_2) can produce such a pattern. This observation firmly established the wave nature of light.[5] Young considered that the wave needs a medium through which to propagate and the concept of the so-called 'ether' was an ideal medium for light to travel through. He also tried to give a (rather unscientific) explanation for phenomena related to the interaction of light with matter.

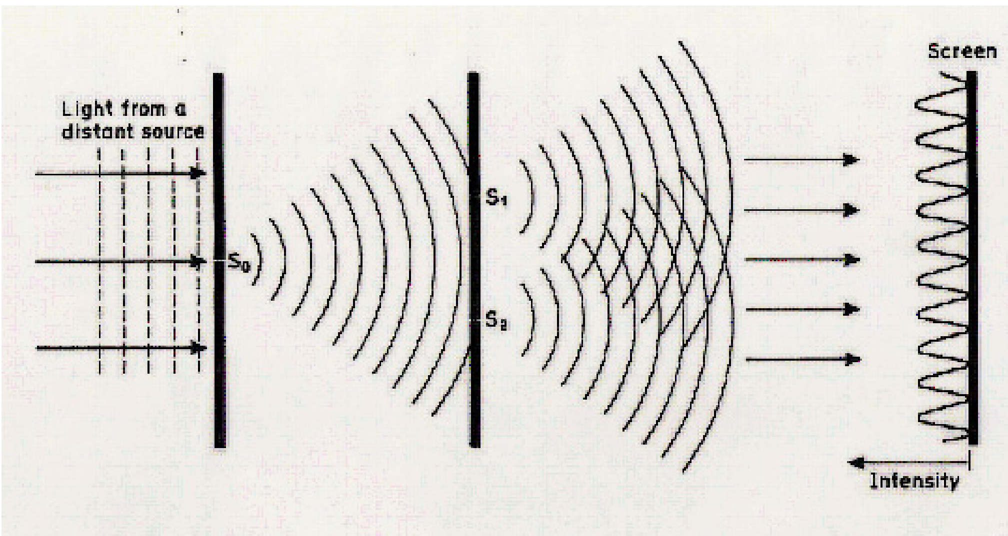

Figure 2. Layout for Young's double-slit experiment.

4 Alain Aspect, From Huygens' waves to Einstein's photons: Weird light. *C. R. Phys*. **18** (2017) 498–503.
5 Anil Anathaswamy, *Through Two Doors at Once: The Elegant Experiment that Captures the Enigma of our Quantum Reality*. Penguin (2018).

Newton essentially imposed the doctrine that the theory of light must, finally, be based on its particulate (corpuscular) nature but Young contradicted this by conclusive and easily reproducible evidence that light is a kind of wave. A wave and a beam of particles are very different things. A particle can exist at one point only at a specific instant of time, whereas a wave pervades a volume of space at any instant of time. It was proved later that the concepts of light as 'wave' and as 'particle' need not be taken to be mutually exclusive, but that sort of duality concept did not exist in the 19th century.

A completely different approach was needed to achieve this understanding ('and' rather than 'either...or'), and it came out of intense research into electricity and magnetism. It was discovered that electricity and magnetism were inexorably interrelated: one can be created from the other. The question of how these forces exert their influence on a neighbouring body through space was raised, and it became necessary to have a word to denote the state of the space surrounding a magnetic pole or an electric charge. The word 'field' was coined. The field was thought to be the manifestation or actuality of a state of tension or of motion in the so-called ether that would not be there if the agent producing it were removed. It was also discovered that the density of electric charges determines the strength of the electric field and the magnitude of electric current flow determines the strength of the magnetic field.

The English physicist and chemist Michael Faraday, after successfully demonstrating the relationship between electricity and magnetism, also succeeded, in 1845, in demonstrating the relationship between light and magnetism.[6] A beam of light was first transmitted through a transparent material having a uniquely oriented crystal structure (polarizer), which was placed in the space between the poles of a very strong electromagnet. It was found that the light intensity changed when viewed through another similar polarizer (now we would call it the analyser) as soon as the electromagnet was switched on. However, a similar experiment by Faraday using a strong electric field failed to show a connexion between the electric field and the transmittance of light. Later it was demonstrate that such a relationship does indeed exist but no electric field of the great strength required was available at that time.

Twenty years later the Scottish physicist James Clerk Maxwell brought Faraday's dream of connecting the electric and magnetic fields and light into reality through a grand unifying mathematical theory—the electromagnetic theory of light.[7] He did not do any experiment, but collected the existing formulae obtained through experiments by Faraday and others and expressed the correlations of the electric and magnetic fields by a set of four equations:

$$\nabla \cdot \boldsymbol{E} = \rho / \varepsilon_0 \tag{1}$$

relates electric field intensity ($\boldsymbol{E}$) to electric charge density (ρ);

$$\nabla \cdot \boldsymbol{B} = 0 \tag{2}$$

relates magnetic field strength ($\boldsymbol{B}$) to magnetic charge (which does not exist, hence equal to zero);

$$\nabla \times \boldsymbol{E} = \partial \boldsymbol{B} / \partial t \tag{3}$$

—a changing magnetic field produces an electric field; and

$$\nabla \times \boldsymbol{B} = \varepsilon_0 \mu_0 (\partial \boldsymbol{E} / \partial t) + \mu_0 J \tag{4}$$

6 Iwan Rhys Morus, *Michael Faraday and the Electric Century*. London: Icon Books (2017).

7 Pericles S.Theocaris & Emmanuel E. Gdoutos, *Electromagnetic Theory of Light* (Springer Series in Optical Sciences, vol. 11). (1979).

—a changing electric field or a static electric current (J) produces a magnetic field. The constants of proportionality, ε and μ are, respectively, the electric (permittivity) and magnetic (permeability) constants of the medium. The subscript 0 attributes the constants to empty space and ∇ is the differential vector operator ($\partial/\partial r$).

Maxwell's equations were found to possess a class of solutions in which the time-varying electric and magnetic fields—one giving rise to the other in turn—detach themselves from the charge or current that produces them and shoot off into space in the form of an electromagnetic wave with a speed given by:

$$c = (\mu/\varepsilon)^{1/2}. \quad (5)$$

Maxwell measured μ and ε for empty space and calculated the speed c of these waves to be ~3×10^8 m/s. This was so close to the measured speed of light (2.99×10^8 m/s) that Maxwell deduced that light must be a form of electromagnetic wave. His concept was very straightforward. If an electrically charged body is shaken up and down it will produce a varying magnetic field in the direction perpendicular to the direction of the shaking. The changing magnetic field will, in turn, create a changing electric field and this process will continue as long as the shaking continues. However, the changing electric and magnetic fields will detach themselves from the charge instantly and travel across the medium or the empty space carrying the energy of the original shaking in the form of the oscillation of the electric and magnetic fields both in time and in space. According to Maxwell, these electromagnetic waves are characterized mainly by the frequency of oscillation of the electric (or magnetic) field. Later it transpired that the electromagnetic radiation encompasses a wide spectrum from high-energy gamma radiation down to low-energy infrared radiation, depending upon the frequency of the field vectors. Light is simply the visible part of the spectrum between the ultraviolet and infrared radiation frequencies (Figure 3).

The infrared is an interesting part of the electromagnetic spectrum for a variety of reasons. It emanates from a hot body and its glow can be seen and felt as heat. Counterintutively, the German physicist Max Planck called a glowing object such as the incandescent filament in a light bulb, a piece of red-hot metal, the sun etc. a 'black body'. Planck took great interest in this topic and in the year 1900, by ingenious trial-and-error, he constructed a formula that correctly related the observed colour, representing the distribution of intensities of a glowing object, such as a piece of heated metal, having a peak wavelength (λ), with the temperature of the body as a parameter (Figure 4). He then tried to deduce the same formula from theoretical considerations. He found out that the only way he could derive such an equation was by making a very fundamental assumption about the way the heated atoms of the object emit light. The assumption was that the atoms do not emit light as continuous waves but as 'wave packets', each carrying a definite energy, E. This energy is proportional to the frequency of vibration, ν, in the wave packet; i.e.,

$$E = h\nu. \quad (6)$$

The constant of proportionality, h is Planck's constant (6.62×10^{-34} J s). He named his wave packets 'quanta' (synonymous with 'particles'), which are also known as 'photons'. The relationship between the frequency of Maxwell's electromagnetic wave and the energy of the associated quantum/photon established the foundation for the unification of the wave and corpuscular concepts of light.[8]

[8] Rodney Loudon, *The Quantum Theory of Light*. Oxford: University Press (2000).

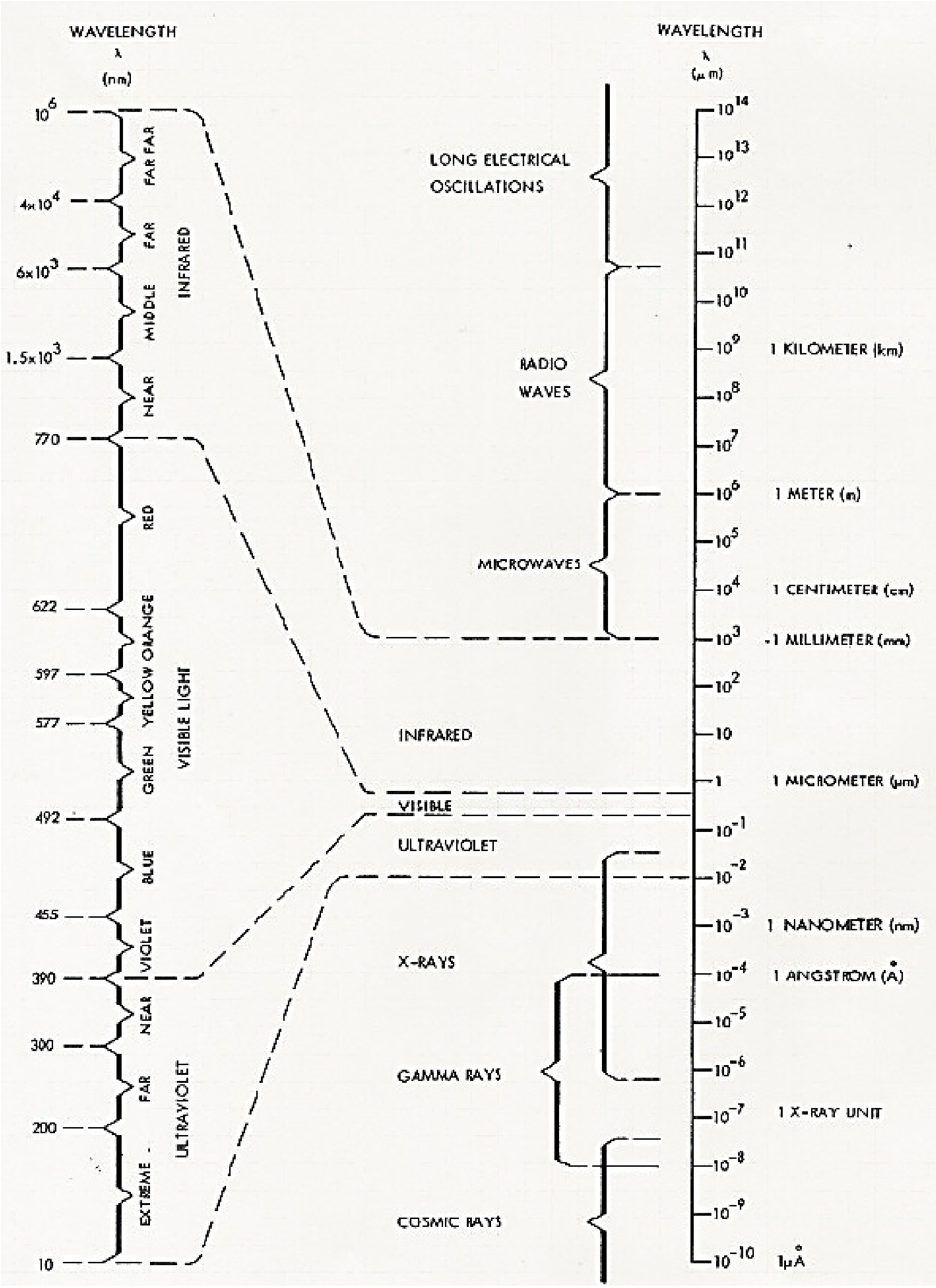

Figure 3. Electromagnetic spectrum: the visible range corresponds to approximately 700–450 nm.

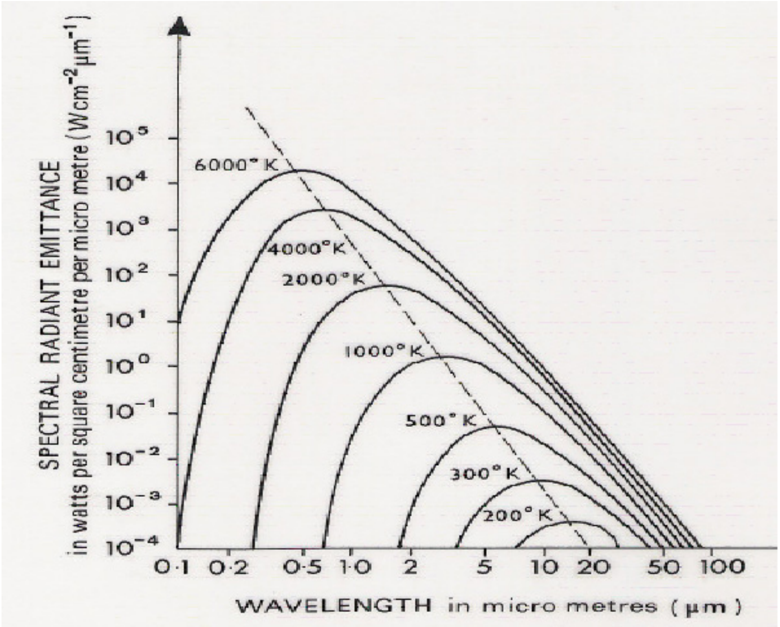

Figure 4. Planck's black body radiation law for objects at different temperatures.

The German-born US physicist Albert Einstein was greatly fascinated by Planck's deduction. He was trying to make a theory for the observed photoelectric effect (ejection of electrons from metal surfaces by light). He also came to the conclusion that, like blackbody radiation, the photoelectric effect also needs the light to be like a stream of particles or quanta. His theory on the photoelectric effect confirmed the corpuscular nature of light[9] and earned him the much-coveted Nobel Prize in 1921. It may be noted that although Einstein is perhaps most famous for his theory of relativity, he received his Nobel Prize for the theory of the photoelectric effect and the nature of light.

As time went by, the hypothesis of light quanta or photons began to be taken seriously. Arthur Compton, a US physicist, in 1922 carried out an experiment with X-ray scattering. He concluded that X-rays bounced off electrons just like billiard balls do from one another.[10] This implied that X-rays are also a part of the electromagnetic spectrum, but having frequencies much higher than those of visible light, and behave like Planck's quanta.

The question was soon asked—can an event generated by a single photon be observed? A single photon is a quantum of energy ($h\nu$) uniquely and discretely (hence quantized) defined by Planck's constant. This means that the electromagnetic field is quantized with discrete

[9] Patrick Bruskiewich, *Albert Einstein and the Photoelectric Effect* (*Elements of Quantum Physics Book 2*). Pythagoras Publishing (2014).

[10] Roger H. Stuewer, *The Compton Effect: Turning Point in Physics*. Cambridge: Science History Publications (1975).

frequency intervals. It did not take long before sensitive photomultipliers were developed that could detect the photoelectric current generated by a single photon. A photodetector can be wired up to produce a clicking sound as soon as a photon hits its surface. Now if an experiment is conducted in a dark enclosure with light from a point source impinging on a very sensitive photodetector it will be observed that the rate at which the clicks are heard diminishes in proportion to the diminution in brightness of the source, but the strength of the sound of the click remains the same. From common sense, it would appear that if the light is a form of wave there would not be any clicks but a continuous buzz; moreover, the sound level of that buzz would decrease as the brightness of the light decreased. These facts provided solid proof that light is nothing but a stream of photons.

Nothing was lacking to prove that light is simply a stream of particles called photons, albeit having an attribute of localized frequency. On the other hand Young's experiment, showing that light is a wavelike flow, had been refined and repeated during more than a century and the evidence that light is a form of an all-pervading wave was still convincing. The situation was unprecedented in the history of science. Simple experiments, requiring no subtleties of interpretation, yielded clear but entirely contradictory conclusions about the nature of light. It was hard to imagine how either Einstein or Young could be wrong or how their concepts of light could be reconciled. Perhaps light is simultaneously a flow of a wave and a stream of particles. If that were true for light, it might also be true for real particles such as electrons, protons, neutrons, alpha particles etc. These may also have associated wave properties. Such inquiries were purely hypothetical until 1925, when the French scientist Louis de Broglie asserted that the nature favours symmetry and if the light wave has corpuscular properties, matter must also have wavelike properties. In analogy to Planck's formula (6) he devised a simple equation linking the momentum p of a particle (mass × velocity) with an associated wavelength λ (lambda) of the so-called 'matter wave',

$$p = h/\lambda \,, \tag{7}$$

h being the familiar Planck constant. Later experiments provided conclusive evidence that particulate matter such as electrons, protons, hydrogen atoms etc. do behave like waves, called 'de Broglie waves', giving diffraction pattern on a screen or photographic plate following propagation through crystal lattices. A diffraction pattern is a series of bright and dark patches resulting from the constructive and destructive combination of two or more waves having different phase angles (cf. Young's experiment, Fig. 2). The wavelengths calculated from such diffraction patterns confirmed the theory proposed by de Broglie.[11]

All these brilliant ideas and experiments did nothing to establish the fundamental connexion between the wave that exists in a region of space (big or small) at any instant of time and the particle that is confined to a point mass at any instant of time. The wave–particle duality remained a puzzle and a subject of discord until scientists came to terms with the fact that the conventional mental picture of the physical world, used to explain observed phenomena, needed to be abandoned. A theory based on a completely different formalism, not supported by any preconceived model of the physical world in terms of particle or wave, was needed to reconcile the duality. In the early 1930s Heisenberg, Schrödinger, Dirac and many other lesser

[11] Louis de Broglie, *An Introduction to the Study of Wave Mechanics*. London: Methuen (1930).

mortals developed such a theory based on a hitherto unknown and unheard 'wave concept'. This theory started with describing the position of electrons in an atom in terms of a wave function. This wave function is, in fact, a mathematical formalism[12] (introduced by Schrödinger and bearing his name) describing the position of an electron in terms of a probability distribution. This wave is *not* a representation of the motion of an electron around the nucleus of an atom, but is to the electron much as Maxwell's electromagnetic wave is to the photon—a particle. But there must be a way to reconcile the concept of a real world particle with a phantom wave. Not all electrons are confined to an atomic sphere and immune from physical observation and manipulation. It was well known that free electrons, away from their atomic shells, move from one place to another, get influenced by electric and magnetic fields and cause counters to register their arrival at particular locations and particular epochs. The electron describes the particle's trajectory in a cloud chamber and its charge can be determined by simple laboratory measurements. Kiel-born German physicist Max Born addressed this ostensive dilemma[13] in 1926. According to his vision this phantom wave does not describe the exact behaviour of a particle, but gives us the probability of finding it at a given point in space at any epoch (instant of time). Born stated, "Paradoxically the motion of an elementary particle obeys the laws of probability, while the probability itself is governed by the causal law". 'Probability wave' is the name coined for this wave and it is characterized by a function with two parameters: amplitude (strength) and phase (angular direction in space), in analogy with real waves.

When all conventional concepts of wave and particles were abandoned and the physical world analysed by a mathematical procedure called 'quantum mechanics', it transpired that the motion of a photon can also be adequately described by this probability wave. Additionally, all the interaction processes between light and matter (e.g., electrons) can be predicted by the use of this mathematical procedure, in its present form known as quantum electrodynamics (QED).

QED is a 'magic box', which emerged into existence out of the confusion amongst the thinkers of the 19th century regarding wave–particle duality. This magic box may be considered to have a shuttered opening for light to enter. If a photodetector is put into the dark magic box and the shutter opened to let in some light, the detector registers the arrival of photons (Figure 5). If, however, two slits and a photographic screen replace the photodetector and the shutter opened to let the light in, the photographic film will record the interference of two light waves emanating from the two slits. This apparent paradox was put onto a firm mathematical foundation by the Danish physicist Niels Bohr, and others, around 1927 during a workshop at Copenhagen, with the result being famously known as the 'Copenhagen interpretation':[14] light propagates through media as a wave and interacts with matter as particles (the wave function collapses to a singularity at the point of interaction).

Let us consider a double-slit experiment where the photons (emitted at a very low rate, i.e. from a very low intensity source) are allowed to go through any of the two slits, S_1 and S_2. Let the wave functions of the photons passing through them be U_1 and U_2 respectively. In this

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[12] Harald J. W. Muller-Kirsten, *Introduction to Quantum Mechanics: Schrödinger Equation and Path Integral* (2nd edn). Singapore: World Scientific (2012).
[13] Max Born, *The Restless Universe* (2nd edn). New York: Dover (2013).
[14] Henry P. Stapp, The Copenhagen interpretation. *Am. J. Phys.* **40** (1972) 1098–1116.

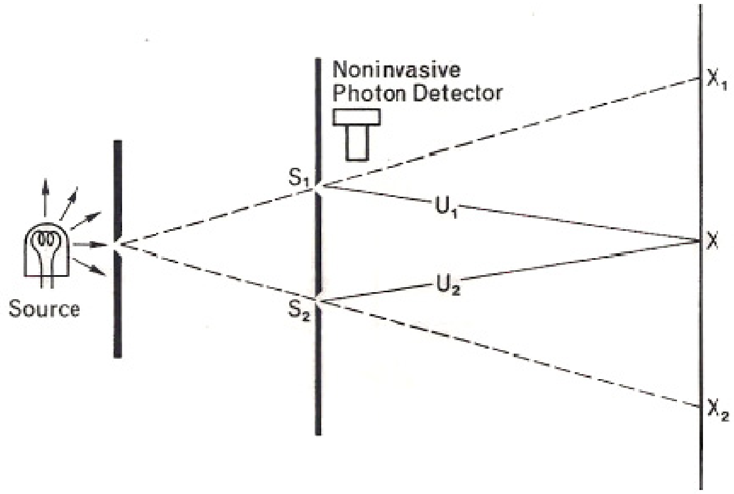

Figure 5. Schematic outline of a thought experiment to demonstrate wave–particle duality.

thought experiment we now introduce a photodetector near one of the slits (say S_1), which is capable of detecting a photon when it passes by (not into) it. Let P be the probability that the detector will detect when a photon is passing by. QED gives an expression for the intensity I_x at a point x on the screen due to the arrival of the photon (the intensity is the square of the probability amplitude):

$$I_x = |\sqrt{(1-P^2)|U_2|^2} + U_1|^2 + P^2|U_2|^2 . \quad (8)$$

Let us consider two scenarios:

i. Perfect detector: $P = 1$; i.e., every time a photon passes by, it registers its presence. Equation (8) then reduces to:

$$I_x = |U_1|^2 + |U_2|^2, \quad (9)$$

implying that the effect on the screen is due to contributions from the two particles (corresponding to two wave functions) that are represented by the combination of two different contributions only, thereby establishing the corpuscular nature of light.

ii. Detector does not work (or is removed) : $P = 0$; the equation is then:

$$I_x = |U_2 + U_1|^2, \quad (10)$$

i.e.

$$I_x = |U_2|^2 + |U_1|^2 + 2|U_1 \times U_2|, \quad (11)$$

implying that the effect on the screen is due to an additional contribution from an interference effect represented by the cross term, establishing the wave nature of light. According to the above formalism, the very act of detecting a photon passing by makes the light behave like a photon. What it further implies is that if in our thought experiment a detector is placed at a point at the centre of the screen and the light intensity (without any background noise) is reduced such that only one photon is allowed to pass through one of the two slits, we would hear clicks. However, if the photodetector is replaced by a screen (or a photographic plate), and exposed over a long time, a fringe pattern will appear. 'Photon' or 'wave': light is what we want it to be. However strange the concept may appear, that is the reality.

As time went on, most physicists learnt to get along with the paradox of the quantum theory. Albert Einstein was not one of them. He believed, to the end of his life, that the probability-based doctrine of Niels Bohr or the Copenhagen interpretation is a superficial resolution and that the real nature of light is still unresolved and the truth lies deeper. His declaration that 'God does not play dice' was opposed to the ideas of Max Born.

In the final analysis, it does not matter what light truly is, as long as we can use it and explain its interactions with itself and matter, albeit using the wonderful magic box called 'QED'. Perhaps light is the essence of all matter and God created it for us to marvel at it but not to be able to comprehend it; like the Holy Grail, an enigma in romance and adventure and never to be found out or understood!