Particles as Waves

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Introduction

The world we live in does not work the way our intuition would have us believe. In reality, all objects have a *dual nature*. They behave as either particles or as waves depending on the circumstances in which we observe them. In this essay we will look at the experiments that led physicists to discover and understand this dual nature as well as the implications this *wave-particle duality* has on the rest of physics.

We will see how what were once considered to be 'sacred' principals of physics, such as *determinism*, have been destroyed by these massive discoveries. The most ground-breaking of these discoveries occurred in the first half of the twentieth century, and turned physics on its head. Whilst being days of glorious discoveries, these were also days of great unease in the physics world. Even some of the greatest minds who made some of the most important contributions to quantum physics and the dual nature of matter (such as Albert Einstein), were unable to accept the eventual profound, and often unsettling, implications of their work.

The classical view

Before the 1600's everything had been thought of as behaving in a particle manner. However, at this point light had not been properly considered. In the seventeenth century, Isaac Newton and Christan Huygens argued over the nature of light, Newton arguing that light behaved in a particle manner (he called the particles of light '*corpuscles*') whilst Huygens claimed that light had a wave nature.

Newton believed light had a particle nature because it appeared to travel only in straight lines, however a small amount of diffraction was observed. (Far more diffraction is observed with lower frequency light such as radio waves, however at the time only visible light was known about.) If light was a wave then the effect of diffraction was expected to be far greater. In order to explain the small amount of diffraction that was observed with visible light he theorised that corpuscles of light could make small waves in the '*luminiferous ether*'. Using Newton's corpuscular theory reflection can easily be explained as the corpuscles bouncing off a surface. However, the explanation for refraction in the corpuscular theory of light says that it is caused by the corpuscles travelling faster in denser mediums when, as would later be discovered, the opposite is true.

At the time, Newton had a greater reputation than Huygens and his theory became more widely accepted. All other fundamental particles were assumed to have a purely particle nature.

Waves take hold

Around the start of the 19th century Thomas Young, a British scientist, performed his infamous double slits experiment (as figure 1 depicts) and showed that visible light did, in fact, diffract and that two coherent sources can interfere with one another to produce fringes. This is strong evidence for the wave nature of light. However, it wasn't until Augustin-Jean Fresnel, a French physicist, published his extensive work on optics, which built on Young's work, showing the wave nature of light, that Newton's corpuscular theory of light was finally abandoned.

In 1850, Léon Foucault performed his experiment to calculate the speed of light in different mediums. He found that light travelled slower in water than in air. This result contradicted Newton's corpuscular theory whilst supporting Huygens' wave theory of light (as water is more dense than air). However, by this time the result was expected. Finally, in 1867, the Scottish physicist, James Clerk Maxwell, released his paper on electromagnetism which was able

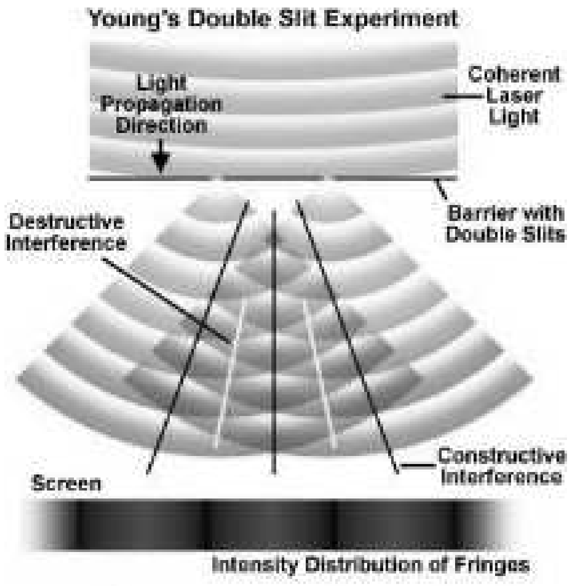

Figure 1: Young's double slits experiment, demonstrates the wave nature of light resulting in interference fringes caused by the interference of the light waves from each slit. Taken from http://www.olympusmicro.com/primer/lightandcolor/interference.html

to explain light in terms of a self-propagating electromagnetic wave through the *luminiferous ether* (the medium that light waves were thought to travel through).

Electrons were first observed in the form of *cathode rays*. When two charged electrodes are positioned at either end of a vacuum tube and the cathode is heated it emits electrons across the tube (known at the time as cathode rays), when the inside of the tube is coated in phosphorescent material, it glows. William Crookes suggested that these cathode rays were caused by some form of disturbance in the supposed *luminiferous ether* ie. waves, as light was thought to be. This view was endorsed when Heinrich Hertz discovered that cathode rays could pass through thin sheets of gold, because their lack of understanding of the atom led them to believe that a particle could not do this.

Back to particles

In 1897, J.J. Thomson was the first person to show that these cathode rays were charged, by showing that they could be deflected by an electric field. He went on to establish the speed at which they were emitted, by considering the case where the 'rays' (although J.J. Thomson already suspected that they were in fact particles) were acted on by both electric and magnetic fields, but where these fields' effects cancelled each other out.

He then went on to show that cathode rays were in-fact particles, because they had mass. He used his previous results to calculate the specific charge of the electron ($\frac{e}{m_e}$). Thomson repeated his experiment with different metals as his electrodes. This had no effect on the result and so he concluded that electrons were fundamental sub-atomic particles. In 1906, he was awarded the Nobel prize for his work.

It was only when the photoelectric effect was fully understood, that light's particle nature was discovered. The first recorded encounter of the photoelectric effect was by Heinrich Hertz, in 1887, when he was producing electromagnetic waves (not necessarily in the visible spectrum) that Maxwell's work had predicted. He discovered that part of his apparatus required a smaller gap in order to spark when shielded by glass (glass absorbs ultraviolet light that would have excited atoms in the metal of his spark gap) than with no shielding. However when shielded by quartz this effect was not seen (quartz doesn't absorb ultraviolet). Whilst his experiments were very successful in their original goal (to produce and detect electromagnetic radiation) he was unable to explain the strange phenomenon saying, "*I confine myself at present to communicating the results obtained, without attempting any theory respecting the manner in which the observed phenomena are brought about.*" This is quite understandable considering that at the time the detailed workings of the atom (such as electron energy levels) were not known.

Once J.J. Thomson publicised his theories on the inner workings of the atom and cathode rays, there was some grounding for understanding the photoelectric effect. It seemed logical that when the light hit the metal the light's energy would cause the electrons to vibrate and aid the electrons in breaking free of the metal. The energy in a wave comes from the amplitude of the wave, so in theory the brighter the light, the more the electrons would vibrate, the faster they would come away from the metal.

In 1902, Philipp von Lenard performed experiments investigating the photoelectric effect, however he found that the behaviour wasn't as predicted by the wave theory of light. He found that increasing the intensity of the light did not increase the kinetic energy of the electrons emitted from the metal but rather that it increased the number of electrons emitted. He went on to find that it was the frequency of the light that governed the kinetic energy of the electrons, - the higher the frequency, the smaller the wavelength, the greater the kinetic energy.

Einstein was the first to properly explain this. He took Max Plank's work on black-body radiation and applied it to light in general. He said that light was not one big wave but rather that it came in packets or quanta (which were later to be known as photons), where the energy of each quanta is dependent on the frequency and is given by:

$$E = h\nu \tag{1}$$

where 'E' is the energy, 'h' is Plank's constant and 'ν' is the frequency of the light in Hertz.

The intensity of the light is dependant on the density of the quanta, which can be thought of as particles. He then went on to describe the photoelectric effect:

$$E = h\nu - \phi \tag{2}$$

where 'E' is the kinetic energy of the electrons emitted from the metal, 'h' is Plank's constant, 'ν' is the frequency of the light in Hertz and 'ϕ' is the '*work function*' of the metal (the minimum energy the electron needs to escape the metal).

Einstein's theory of light was the first example of a crude wave-particle duality, however it was many years before his theory was accepted, as the idea of a particle theory of light seemed absurd considering all the evidence for light being a wave. An American scientist called Robert Millikan didn't accept Einstein's theory as he saw it as an attack on the wave theory of light and worked for years on the photoelectric effect in the hope of disproving it. He referred to Einstein's theory as "*semi-corpuscular*", and in later years explained his feelings on Einstein's theory, "*I was compelled in 1915 to assert its unambiguous verification in spite of its unreasonableness ... it seemed to violate everything we knew about the interference of light.*"[1] Millikan's results actually supported Einstein's theory although he later won the Nobel prize for measuring Plank's constant to within 0.5% (and also accurate measurement of the charge on the electron).

[1]Taken from John Gribbin's "*In search of Schrödinger's Cat*" (page 82) who in turn took the quote from A.Pais's "*Subtle Is the Lord*".

Wave-particle duality

To begin with, the two 'natures' of light (wave & particle) were seen as contradictory and mutually opposing, It was Louis-Victor de Broglie who first thought that these two natures could simply be two aspects of a single nature, "*Two seemingly incompatible conceptions can each represent an aspect of the truth ... They may serve in turn to represent the facts without ever entering into direct conflict.*"[2]. He was also the first person to properly consider the idea that particles (or what were thought to be well-behaved classical particles, such as electrons) could also have this supposed dual nature. He derived the 'de Broglie wavelength' which is given by:

$$\lambda = \frac{h}{\rho} \tag{3}$$

where 'λ' is the wavelength, 'h' is Plank's constant and 'ρ' is the momentum of the particle.

As the larger the length of a wave the more apparent *wave-like* properties are (consider diffraction), this means that the smaller the momentum of the particle the more wave-like its nature is. So low mass, slow moving particles are the most wave-like. Electrons therefore will show their wave properties much easier than protons. What were once thought to be well-behaved particles can actually be diffracted, however they need very small gaps in order to do this as they have far smaller wavelengths than light does. Electrons can be diffracted using crystals - the gaps between the atoms are just small enough. In the early 1920's two American physicists, Clinton Davisson and Charles Kunsman observed this effect before de Broglie released his hypothesis. At the time they believed the diffraction effect was due to collisions between the electrons and the atoms in the crystals. The idea that electrons could behave like waves was very alien and it wasn't until Erwin Schrödinger formulated a new theory on the inner workings of the atom, that used and extended de Broglie's ideas, that it was taken seriously and further experiments were performed. One of the people who verified the wave nature of electrons was George Thomson (the son of J.J. Thomson), and in 1937 he shared the Nobel prize for this with Davisson - leading to the great irony that the father had been awarded the Nobel prize for proving the particle nature of electrons whilst his son would later be awarded it for proving the wave nature! At first glance, it seems that one of those awards must be unjustified, but both discoveries and both contributions are great

[2]A quote of de Broglie taken from the free on-line Wikipedia Encyclopedia, http://en.wikipedia.org/wiki/Louis-Victor_de_Broglie

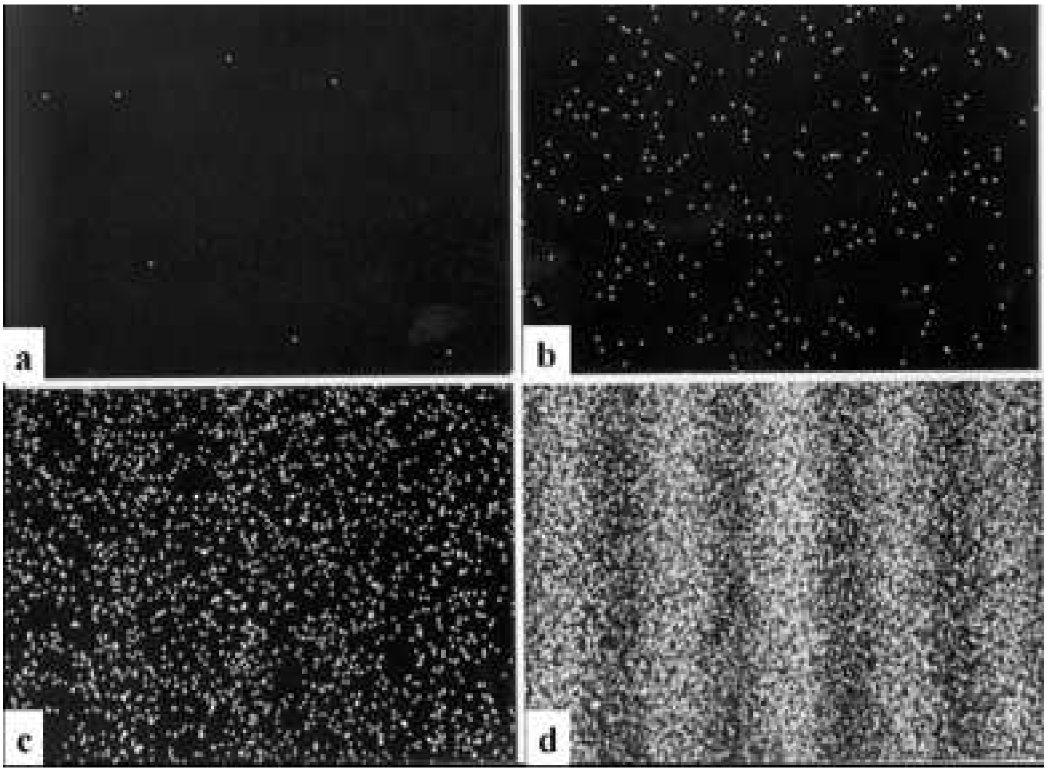

Figure 2: Snapshots of the results taken at different times. As the experiment progresses we see the diffraction pattern build up as defined by the interference of the probability waves. Taken from http://www.hqrd.hitachi.co.jp/em/doubleslit.cfm

and important to understanding the true nature of matter. In later years both neutrons and protons were found to have wave natures, and in fact wave-particle duality can be extended to all matter.

This wave nature of electrons is not limited to electrons in transit; stationary electrons in atoms have *wave-functions* rather than definite positions when they are not observed. It is these wave-functions that form the electron energy levels in atoms and govern chemistry. Schrödinger formulated his infamous *wave-equation* in the mid-1920s and Max Born later used it to tie the wave and particle natures of matter together. He found that the square of the wave-function at any specific point of a particle was related to the *probability* of finding the particle in that position. This 'probability-waves' approach can be proved by diffracting particles through a slit one by one. Over time the usual diffraction pattern builds up.

In fact a group of Japanese scientists have actually performed this experiment (which is usually considered a *thought experiment*). They performed the equivalent of Young's double slits experiment but with a slow stream of electrons. Figure 2 shows the results observed in this experiment.[3]

This leads to a fuller understanding of so called *wave-particle duality* in that, in general, matter behaves as a wave until it is actually observed, when its wave function is said to 'break down' and the particle 'chooses' a position governed by chance, defined by the square of its wave function at the time. When matter is observed it is seen as a particle with a definite position. This bizarre 'true nature' leads on to some mind-blowing behaviour. Because of this nature, classical thinking has some pitfalls at the quantum level and the *Copenhagen interpretation* is often employed to help us avoid them.

The Copenhagen interpretation

The Copenhagen interpretation is the result of a gathering of key ideas in quantum physics, a great deal of which was formed by Niels Bohr and Werner Heisenberg, who built on Max Born's probability waves theory, whilst collaborating in Copenhagen.

Classical thinking encourages us to try and find a completely deterministic set of rules underneath quantum physics whose outcome is governed by mere probability to which the Copenhagen interpretation replies, "*The probability statements made by quantum mechanics are irreducible in the sense that they don't just reflect our limited knowledge of some hidden variables. In classical physics, probabilities were used to describe the outcome of rolling a die, even though the process was thought to be deterministic. Probabilities were used to substitute for complete knowledge. By contrast, the Copenhagen interpretation holds that in quantum mechanics, measurement outcomes are fundamentally indeterministic.*"

Our intuition from classical experiments also leads us to think that it's okay to ask questions about the behaviour of things when we aren't observing them. However the Copenhagen interpretation tells us that, "*Physics is the science of outcomes of measurement processes. Speculation beyond that cannot be justified... Questions like "where was the particle before I measured its position" are meaningless.*"

It also clearly explains how the statistics of the wave function is transfered into an outcome via observation, "*The act of measurement causes an instantaneous "collapse of the wave function". This means that the measurement process randomly picks out exactly one of the many possibilities allowed for*

[3] At the time of writing a web-page is available explaining the experiment at http://www.hqrd.hitachi.co.jp/em/doubleslit.cfm where a video clip can be downloaded showing the diffraction pattern building up in real-time.

by the state's wave function, and the wave function instantaneously changes to reflect that pick."[4]

The Copenhagen interpretation helps to draw the line between physics and philosophy. It's okay to discuss what particles might be doing while you aren't looking at them. However it's important to realise that this is not physics, its closer to a form of philosophy. Heisenberg himself wrote a book entitled "*Physics and Philosophy*". The Copenhagen interpretation and the dual nature of matter raise many philosophical questions besides what something is doing when you aren't looking at it, such as "*What constitutes an observer?*" etc...

It also explicitly mentions that observing a system affects its behaviour (as we will see later); the system and the observer are not independent of one another and so the observer becomes a part of the system.

The fact that the probabilistic equations are irreducible also destroys determinism as we cannot know for sure where a particle will turn up. This is a concept that even the founders of quantum physics found hard to accept, most notably Einstein who is famously quoted as saying to Max Born in a letter that "*God does not play dice*".

Weirdness and beauty

In order to show both the mind-boggling and the beautiful in the 'true nature' of matter, I'm going to discuss two thought experiments and their expected results. From a classical point of view they are practically the same experiment and we would expect identical results. However, the Copenhagen interpretation teaches us differently and we will see both why they are considered very different experiments and why we cannot assume they will have the same results.

The particles in these experiments could be anything, but for the purpose of this essay, we will assume they're electrons. These experiments are variations on Young's double slits experiment as they use electrons rather than light.

Figure 3 shows our first thought experiment. An electron beam is passed through the Young's double slits apparatus. The electrons are not observed until they reach the screen, the results are much the same as Young's original experiment with light. We have no idea about the electrons' behaviour in getting from the source to the screen. The 'electron waves' pass through

[4] The quotes, structure and ideas in these three paragraphs are closely based on the Wikipedia page on the Copenhagen interpretation at the time of writing, which can be found at http://en.wikipedia.org/wiki/Copenhagen_interpretation

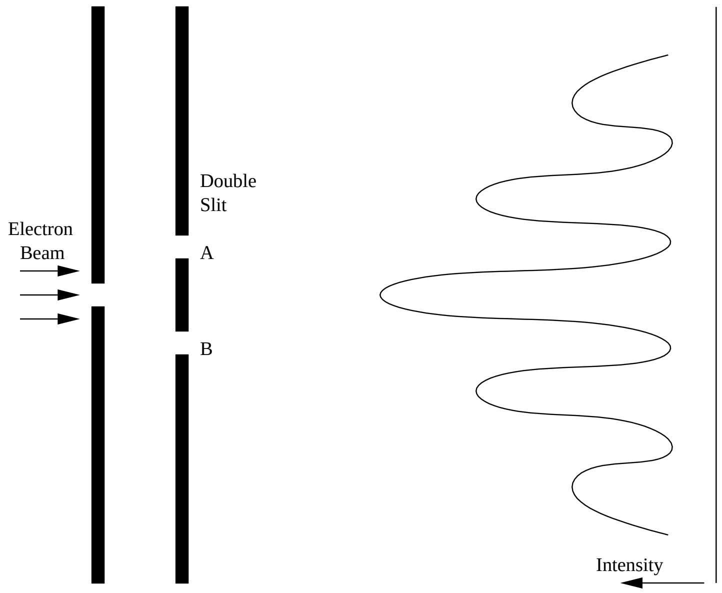

Figure 3: The first experiment setup and approximate results. The probability waves interfere with one another and cause the interference pattern.

both slits and the resulting waves then interfere with one another to produce the probability distribution of electrons observed on the screen.

Figure 4 shows our second experiment. This is a separate experiment from the last one, as we are observing which hole each electron passes through in its path to the screen. In classical physics this would be seen as much the same experiment as it would not be thought to influence the results; however, we know from the Copenhagen interpretation that observing the experiment affects it and so we have no right to expect the same outcome and indeed we do not. When we observe which hole each electron passes through we break down its wave-function and so the probability waves cannot interfere with one another (as the 'electron wave' only passes though one slit) and we don't see an interference pattern but rather simply two slightly overlapping peaks of electrons. This is much more like what we would expect from the old particle-nature model.[5]

[5] Figures 3 & 4 were inspired by a similar diagram in John Gribbin's "*In search of Schrödinger's Cat*" on page 167

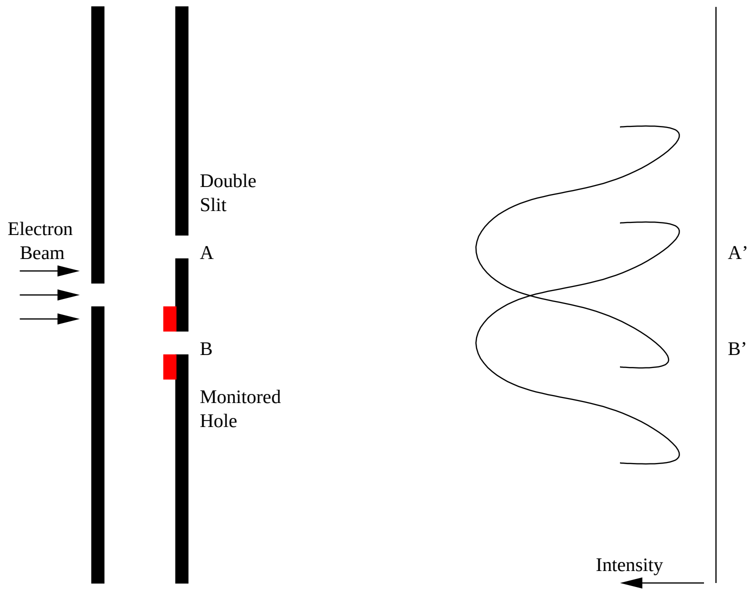

Figure 4: The second experiment setup and approximate results. The wave function of the particles is broken down at the holes, we know which slit the particle passes through and so we do not find the interference pattern.

Conclusion

The nature of all matter (including light) is described as both wave and particle. However, really there is only one nature to matter and we can draw parallels to two macroscopic natures that we understand, namely wave and particle. When a particle is not being observed, it has a wave nature and its position is not certain. When it is finally observed, it chooses a position depending on the probability distribution defined by the square of its wave-function. This is known as the 'breakdown of the wave-function'. As the Copenhagen interpretation tells us, we cannot know what a particle is doing when we aren't looking at it, and when we do look at it we affect its future; experiments can have very different results depending on what is observed. Due to the fundamental dependence of nature on probability (the equations governing this are irreducible) the universe is indeterministic, and the future could not be predicted completely even if you knew the position and momentum of every particle exactly.

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