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Hidden Waves

Since the publications of Newton's Corpuscular Theory of Light in 1637 and Christiaan Huygens' Wave Theory of Light in 1678 (Toyoda and Ohtake, 2020), the physics world has deliberated over the true nature of light—is it a wave or a particle? The debate, thought to be resolved in the nineteenth century when Thomas Young proved Huygens' theory using Wave Interference was reignited in 1887 by a phenomenon known as the "Photoelectric Effect", where light did not exhibit properties true to the Wave Theory of Light. The deliberation was only resolved by Albert Einstein in 1905, whose revolutionary publication gave rise to a new set of physical laws: Quantum Mechanics (Toyoda and Ohtake, 2020).

In essence, Einstein predicted that light was not one continuous wave, rather it was broken down into discrete packets of energy known as quanta, which can exhibit either the properties of a wave or a particle (Ohsuka, Toyoda, Takamoto and Ohtake, 2020). Einstein's proposition stated that the energy of a light quantum, or photon, is proportional to its frequency multiplied by Planck's Constant— a number introduced by Max Planck in his solution for blackbody radiation in 1900.

By definition, a black body is a theoretical object that would absorb all electromagnetic radiation that falls upon it, which is why it would be perceived as black in colour. The law of the conservation of energy, however, requires that all this energy must somehow be released—it cannot just disappear. Therefore, the body emits the energy in the form of thermal radiation (Blackbody Radiation | COSMOS, 2020). The problem was that no classical theory seemed able to accurately describe the rate at which radiation was being released. Planck's solution was that the radiation was released in specific quantities known as quanta and introduced his famous constant.

It was not until Einstein brought about his solution to the photoelectric effect that the true significance of Planck's discovery began to be realised. However, only when Louis de Broglie hypothesised that all particles—including those which construct matter—exhibit wave-particle duality (What Is the De Broglie Hypothesis?, 2020), that the true significance of the arising Quantum Mechanics was realised. Over the course of the following century, many of the known laws of physics were revised and "quantised" in accordance with the new Quantum theories. The arising theory was so revolutionary that Einstein himself was quoted saying, "If it [quantum theory] is correct, it signifies the end of physics as a science." (Quantum Quotes, 2020).

Following the realisation that all particles exhibit secret wave properties and can behave as both a wave and a particle, physicists sought to find an equation that determined the behaviour of quanta, involving both its wave and particle behaviours. This equation was discovered by Erwin Schrödinger in 1926:

$$\mathrm{E}\Psi(x) = \frac{-\hbar^2}{2m}\frac{d^2\Psi(\mathrm{x})}{dx^2} + V\Psi(x)$$

(Up and Atom, 2020)

Unlike classical Newtonian Mechanics, the Schrödinger Equation is only able to give a set of probable descriptions of how an isolated quantum system will evolve; the true path is never able to be accurately predicted. This idea was deemed preposterous by Einstein, who was quoted saying, "God does not play dice with the universe." (Dickerson, 2020).

A system which evolves over time will have a number of possible quantum states, some more probable than others; it is impossible to truly know the path of a quantum system, rather one can only predict the paths in which it *may* have taken (Professor Dave Explains, 2020). As a result, until quantum systems are observed, quanta are not assumed to be following one specific journey through space, rather it is assumed they are following *all* possible journeys instantaneously—in a "superposition". The wave function $\Psi(\mathrm{x})$ of the Schrödinger Equation determines the size and shape of this superposition and returns the probability distribution of the system—which happens to have wave-like characteristics. When observed or measured, the wave function of the system collapses, the probabilities reducing to one and the quanta are revealed to be residing in one specific place (wave function in quantum mechanics | Quantum Physics Lady, 2020).

Using the classical relationship of the total energy of a system, $TE = KE + PE$, Schrödinger was only able to find the kinetic and potential energies of a quantum system's probability distribution, given by the wave function. This successfully solved for the total energy of the system and giving all the possible details about the quantum system and the hidden state of its quanta. (Up and Atom, 2020).

No prediction in Quantum Mechanics, however, was as shocking as a principle proposed by Werner Heisenberg. Known as the Uncertainty Principle, it states that by observing the position of a quantum, we are altering its momentum or vice versa; more specifically, the more accurately of a particle is known, the less accurately its momentum can be known (Uffink, 2020). As an example, somebody wants to measure the position of a quantum, therefore they decide to shine light over it, its shadow revealing its position. Although this experiment may accurately find the position, it requires photons to bounce against the quantum, altering its momentum (Hawking, n.d., p. 62, 63). Therefore, the true nature of the quantum remains "hidden" from the observer.

As a consequence of the Uncertainty Principle, the greater one knows more of a quantum's particle-like properties, the less they will know of its wave-like properties, thus it is impossible to know both natures of a quantum at one moment (Hawking, n.d., p. 62, 63).

One problem of the Uncertainty Principle, however, was that it required that all places in space to have uncertain properties. This, however, requires that empty space, or places thought to have no energy, to have uncertainty. As energy can only be transported by quanta, areas of the universe once thought to be empty are in fact full of quanta in phenomenon known as vacuum fluctuations (Hawking, n.d., p. 120, 121).

Uncertainty Principle allows for quantum fields to "borrow" small amounts of energy. This causes a positive excitation in the field (perceived as a quantum) to appear, however its existence is governed by the Uncertainty Principle. Due to the conservation of energy's requirement that energy can never be create nor destroyed (Conservation of Energy, 2020), at the point in the field where the positive excitation appeared forms a negative-energy excitation. This negative-energy excitation can be perceived as a negative-energy antiparticle, and when the pair collide, the excitations in the field annihilate one another and the return to zero, the quanta disappearing (Hawking, n.d., p. 120, 121). "Real" particles, such as the electron and its antiparticle, the positron, can also annihilate, their energy transforming into two gamma rays; photons can also separate into an electron-positron pair (Britannica.com, n.d.).

Although vacuum fluctuations generally don't affect the universe, there are a few circumstances where their existence is vital. An example of this is near black holes, where the existence of vacuum fluctuations is essential for the gradual evaporation of the black hole. When a particle-antiparticle pair appear near the event horizon of a black hole, there is a chance that either one or both of the particles may fall into the black hole. If one of them were to fall into the black hole, it must be the negative energy antiparticle, as the laws of thermodynamics do not permit the existence of negative-energy quanta for extended periods of time. The gravitational strength of the black hole takes enough energy away from the quantum for it to become a “real” particle, before falling into the black hole. This then causes the black hole to lose mass in accordance with $E = mc^2$ (Hawking, n.d., p. 121). The partner, if it escapes, becomes a real, free quantum. This phenomenon, known a “Hawking Radiation”, eventually leads to the complete evaporation of the black hole.

Furthermore, virtual quanta are constantly being transmitted between real quanta. Used to mediate three of the four fundamental forces of nature, electromagnetism, strong interaction and weak interaction (plus the Higgs field), special types of quanta known as bosons act as messengers and are exchanged between real quanta in order to communicate. (Scientific American, 2020). An example of this is with electromagnetic repulsion, where a virtual photon mediating the electromagnetic force, is exchanged between two negatively charged electrons, causing them to repel.

In conclusion, the universe is full of hidden waves. After centuries of debate, it was only Einstein and Planck who realised the true nature of light. From there came a quantum revolution, in which everything in the universe was realised to exhibit secret wave properties. The universe, however, was realised to only be governed by chance and uncertainty. This, however, allows secret waves to jump into the universe, before colliding with their partner and disappearing. Without these hidden waves, fundamental processes such as black hole evaporation and mediation of the four fundamental forces could not take place. As said by Stephen Hawking, “Not only does God play dice, but... he sometimes throws them where they cannot be seen.” (Stephen Hawking Quotes, 2020).

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