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Evolution and Foundations of Quantum Mechanics: A Narrative Review of Milestones and Concepts

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Abstract: ***This narrative review traces the conceptual and experimental evolution of quantum mechanics, beginning from the inadequacies of classical physics to explain phenomena like blackbody radiation and the photoelectric effect. It highlights pivotal developments, including Planck's quantum hypothesis, Einstein's photon theory, Bohr's atomic model, and the establishment of wave-particle duality through de Broglie and Schrödinger's work. The review also delves into the philosophical implications of quantum theory, including the observer effect, uncertainty principle, and quantum entanglement. Through a cohesive historical lens, the article articulates the transformative journey of quantum mechanics into a fundamental pillar of modern physics.***

Keywords: quantum mechanics, wave-particle duality, Schrödinger equation, uncertainty principle, quantum entanglement

1. Introduction

Quantum mechanics is the appropriate framework to study microscopic particles such as molecules, atoms, and subatomic particles which has been extensively applied over the past century by theoretical physicists across various fields. It has often led to surprising at time, shocking results which have been found sooner or later to be stunningly true. No wonder, people say "If you go through quantum mechanics and if you are not confused, then you have not gone through it 'properly'. It is not the view held by its well-known critics like Albert Einstein but by its well-known proponents like Niels Bohr and Richard Feynman.

This article aims to narrate the historical and conceptual development of quantum mechanics by examining key experiments, theories, and philosophical implications that shaped the modern understanding of microscopic phenomena.

Highlighting these foundational advances is crucial for appreciating the evolution of modern physics and for guiding contemporary studies in quantum technologies, education, and theoretical modelling.

Why Was Quantum Mechanics Needed?

By the middle of 19th century, classical mechanics and classical electrodynamics were supposed to explain everything related to matter and radiation. The former was believed to exhibit a discrete, particle-like nature, while the latter demonstrated a continuous wave-like nature. But in the second half of 19th century, several experimental results came to light, which the classical physics was unable to explain. Some of these were:

a) The spectrum of black-body radiation
b) The photoelectric effect
c) The structure of atoms and their spectra.

1) Spectral distribution of energy in black body radiation: -

The distribution of energy among the various wavelengths in black body radiation was investigated by Lummer and Pringsheim in 1899. They measured **spectral radiancy E_λ**, which is defined such that the quantity $E_\lambda d\lambda$ is the energy of the wavelengths lying between λ and $\lambda + d\lambda$ emitted per second per unit surface area of the black body. It is found that E_λ goes to zero as $\lambda \to 0$ as well as when $\lambda \to \infty$. In between E_λ passes through a peak. The value of λ where E_λ is maximum at a given temperature decreases with increase in temperature.

Rayleigh and Jeans using classical ideas arrived at a distribution law:

$$u_\lambda d\lambda = \frac{8\pi kT}{\lambda^4} d\lambda$$

This agrees with experiment only at long wavelength but fails miserably at short wavelength. In fact, $u_\lambda \to \infty$ as $\lambda \to 0$. This divergence known as ultraviolet catastrophe is completely erroneous.

Another classical formula obtained by Wien is

$$u_\lambda d\lambda = \frac{A}{\lambda^5}\, e^{-\frac{B}{\lambda T}}\, d\lambda\ ;$$

with A and B as arbitrary constants.

It was in better agreement with experiment. But it was found that even with most suitable values of A and B, Wien's law agreed with experiments only at small wavelengths.

At this stage Max Planck [1] made two bold and (at that time) unbelievable postulates:

- The exchange of energy between the walls of a black body cavity and the radiation can take place only in bundles(quanta) of energy.
- The energy in each bundle is directly proportional to the frequency, ν of the radiation; i.e. $\varepsilon_0 = h\nu$ where 'h' is a constant called Planck's constant.

At the time, even Planck firmly believed that energy was continuously distributed. Planck was unhappy with his postulates called it an act of desperation. But he arrived at a distribution law

$$u_\nu d\nu = \frac{8\pi\nu^2 d\nu}{c^3} . \frac{h\nu}{\exp\left(\frac{h\nu}{kT} - 1\right)}$$

which exactly reproduces the experimental result. On 14th December, 1900, while proposing his "quantum theory" Planck hardly realized that he had given birth to a new branch of physics now developed as powerful quantum mechanics. By fitting with the experimental data the value of Planck's constant, h, is found to be 6.63×10^{-34} Joule.sec which is so small that unless ν is very high, the quantum of energy will be so small that the discreteness of energy will not be revealed. Planck was awarded Nobel prize in 1918 for "Discovery of the elemental quantum".

2) Photoelectric Effect:

Much before Planck proposed his 'quantum theory', several experiments established that when light of high frequency falls on the surface of metal with low work function electrons are emitted. This phenomenon known as photoelectric effect has the following features which the classical wave theory of light could not explain:

a) When the frequency of light is less than threshold frequency, ν_0, which is a characteristic of the metal, no electron is emitted whatever may be the intensity of light.
b) The maximum kinetic energy of the emitted electron is directly proportional to $(\nu - \nu_0)$, where ν is the frequency of incident light, but is independent of intensity of light.
c) Increasing the intensity of light increases the photoelectric current provided the frequency of light is greater than threshold frequency.
d) The emission of photoelectrons is instantaneous (the time lag is less than 10^{-9} s).

Albert Einstein [2] extending the quantum concept of Planck considered the interaction of light with metal as a collision between quantum of energy (called photon) and atomic electron. A photon on collision gives its whole energy to the electron or none at all. Thus, he obtained the expression for maximum K.E. of emitted electron as

$$K_{max} = h\nu - \phi = h(\nu - \nu_0)$$

where $\varphi = h\nu_0$ is work function of metal. This equation known as Einstein's photoelectric equation successfully explains the photoelectric effect and fetched Einstein Nobel prize in 1921.

A photon with energy $h\nu$ possesses linear momentum $\frac{h\nu}{c}$ and zero rest mass. As it always moves with speed c (in vacuum), it has a mass $m = \frac{h\nu}{c^2}$. These properties of photon as a particle were confirmed by (i) Compton effect (1923) and (ii) Pound–Rebka experiment in 1960.

a) **Compton Scattering:**

In 1923 Arthur Compton [3] at Washington University carried out an experiment that gave solid support to the view that both energy and momentum are transferred via photons. He arranged a beam of X-rays of single wavelength λ to fall on a target made of Carbon(graphite) and measured the wavelength and intensities of the scattered X-rays in various directions. He found that scattered X-rays contain a range of wavelengths with two prominent intensity peak, one centered about the incident wavelength λ and the other about a higher wavelength $\lambda' = \lambda + \Delta\lambda$.
The "Compton shift", $\Delta\lambda$, varies with angle at which the scattered X-rays are detected.

Compton interpreted the result as a collision between incident photon and loosely bound electron in the carbon target. After collision electron recoil and scattered photon has less energy. Using the principle of conservation of linear momentum and energy, one finds the Compton shift as a function of scattering angle ϕ;

$$\Delta\lambda = \frac{h}{mc}(1 - cos\phi)$$

This explains the peak at the shifted wavelength, $\lambda + \Delta\lambda$. The peak at the original wavelength, λ is interpreted as arising from a collision between incident photon and tightly bound electron of carbon atom. Mass of a carbon atom, being about 22,000 times than that of electron, for such collisions $\Delta\lambda$ is about 22,000 times smaller, too small to be detected.

Compton was awarded Nobel prize in 1927 for "Discovery of the scattering of X-rays by charged particles".

In 1960, Pound and Rebka verified experimentally that a photon of frequency, ν in free fall under gravity behaves as a particle of mass, $m = \frac{h\nu}{c^2}$. We know that a particle of mass, m, falling freely through a height, H, acquires an energy, mgH. Since the velocity of photon cannot increase, its frequency should increase to ν' so that

$$h\nu' = h\nu + \frac{h\nu}{c^2}gH = h\nu\,(1 + \frac{gH}{c^2})$$

or

$$\nu' = \nu\,(1 + \frac{gH}{c^2})$$

In their experiment, H = 22.5 m and $\nu = 7.3 \times 10^{14}$ Hz

Thus, $\nu' - \nu = \frac{\nu gH}{c^2} = 1.8$ Hz

This amount of increase in frequency was obtained by Pound and Rebka.

Successful explanation of black body radiation, Compton effect, photoelectric effect etc. confirm particle nature of electromagnetic radiation. At the same time, explanation of phenomena like interference and diffraction require that electromagnetic radiation be treated as wave. Thus, we conclude that electromagnetic radiations have dual nature. However, it is not possible to see both natures simultaneously. These are like two sides of a single coin, mutually exclusive.

b) Single photon double-slit experiment:

A single photon version of Young's double slit experiment was first carried out by G.I. Taylor in 1909 and since then repeated many times. It differs from the original double-slit experiment in that the light source is so weak that it emits only one photon at a time, at random intervals. If the experiment runs long enough (several months for Taylor's early experiment) interference fringes still, build up on screen.

If a tiny photon detector (a photoelectric device that clicks when it absorbs a photon) is set up at a point on the screen, it produces a series of clicks randomly spaced in time. If the detector is slowly moved up or down on the screen, the click rate is found to increase and decrease, passing through alternate maxima and minima that correspond exactly to the maxima and minima of the interference fringes.

The result cannot be explained by considering only the particle or only the wave nature of light. We know that photons manifest themselves only when light interacts with matter, hence we can think that photons originate in source and vanish in detector but in between light travels as wave. That seems to be a satisfactory explanation.

According to Richard Feynman "The single photon double-slit experiment is a phenomenon which is impossible to explain in any classical way and which has in it the heart of quantum mechanics".

c) Structure of atom and origin of atomic spectra

Though concept of atom was established by Lavoisier and Dalton in 1810, its structure remained a mystery even till the beginning of 20^{th} century. In 1911 Ernest Rutherford on the basis of result of an experiment suggested by him and carried out by his coworkers Geiger and Marsden, proposed that entire positive charge and most of the mass of atom is concentrated in a small region near its centre forming its nucleus. In their experiment, energetic α-particles were directed at a thin gold foil, and the deflection of these particles was measured. Though most of the particles were deflected through small angles, few of them (1 in 8000) deflected surprisingly large angles (close to 180°) deflection. In Rutherford words "It was quite the most incredible event that ever happened to me in my life."

Rutherford also postulated that electrons perform circular motion outside the nucleus, the Coulomb attraction providing the necessary centripetal force. However, the model of Rutherford failed to provide stability to the atoms and to explain the emission of characteristic discrete frequencies by the atoms.

Experimental works starting from Fraunhofer in 1814 to Kirchhoff in 1850 led to the conclusion that every element or compound produces a characteristic pattern of spectral lines.

In 1885 Balmer suggested an empirical formula that the wavelengths of spectral lines are found to satisfy

$$\frac{1}{\lambda_{m,n}} = K\left(\frac{1}{m^2} - \frac{1}{n^2}\right); \text{n} > \text{m}$$

where K is a constant specific to element involved and m, n are integers.

In 1913 Niels Bohr proposed a new atomic model based on following postulates:

1) Electron in an atom moves in circular orbit round the nucleus with Coulomb force providing the centripetal force.
2) Electron moves only in such non-radiating (stationary) orbits for which the magnitude of orbital angular momentum is an integral multiple of $\hbar$ $(\frac{h}{2\pi})$
3) An electron having total energy E_i in i^{th} orbit may jump to j^{th} orbit of lower energy E_j by radiating one quantum (photon) of energy $h\nu = E_i - E_j$. It can also absorb a photon of energy $h\nu$ to jump from j^{th} orbit (of lower energy) to i^{th} orbit (higher energy).

Bohr thus obtained the expressions for radius of electronic orbit, r_n, speed of electron, v_n and its total energy, E_n , in nth orbit for a hydrogen like atom as

$$r_n = \frac{n^2\hbar^2}{mZe^2}$$
$$v_n = \frac{Ze^2}{n\hbar}$$
$$E_n = -\frac{Z^2e^4m}{2n^2\hbar^2}\text{; n=1, 2....}$$

Bohr model was able to explain successfully the Balmer's formula. The existence of discrete energy levels in atoms was experimentally proved by Franck and Hertz [4] in 1914.

Bohr was awarded Nobel prize in 1922 for "Study of structure and radiations of atom". Despite its tremendous success, Bohr theory has following limitations:

1) With Bohr model it is not possible to calculate the intensities of various spectral lines emitted by hydrogen atom.
2) Bohr model though partially successful for monovalent alkali atoms fails for other multi-electron atoms.
3) It was difficult to explain why accelerated electrons would not radiate in some orbits. In spite of these limitations the Bohr atomic model was a giant step in the understanding of atomic physics and paved the way for quantum mechanics.

Matter waves:

Louis de Broglie [5], in his Ph.D. thesis submitted in 1924, put forward an epoch-making hypothesis based on following simple arguments: "Nature favours symmetry. If radiation possesses dual characteristics, why should matter be an exception?"

He suggested that a wave (matter wave) can also be associated with a particle in the same way as a particle (photon) is associated with radiation. He also suggested that just like photon a material particle (say electron) of energy E and momentum p should be associated with a matter wave of frequency, $\nu = \frac{E}{h}$ and wavelength $\lambda = \frac{h}{p}$. For non-relativistic electron with E (in eV), we have $\lambda = \frac{12.25}{\sqrt{E}} A$

de Broglie used the concept of matter waves to provide a proof for Bohr's postulate of non-radiating orbits. He argued that for stationary orbit electron wave should form a standing wave pattern. For this

$$2\pi r_n = n\lambda_n = \frac{nh}{p_n}$$

Thus $p_n r_n = n\hbar$; which is Bohr's postulate of quantization of angular momentum. It is said that Einstein was impressed by the above proof and forwarded the thesis to Schrödinger which proved the existence of wave mechanics.

The existence of matter waves and de Broglie relations were experimentally confirmed in 1927 by C.J. Davisson and L.H. Germer [6] and also by G.P. Thomson [7] by observing diffraction of electrons like x-rays. de Broglie was awarded Nobel prize in 1929 for "proposing wave nature of electrons".

Davisson and G.P. Thomson both shared Nobel prize of 1937 for "Discovery of Diffraction of Electrons by Crystals". It is an interesting coincidence that Sir J.J. Thomson established experimentally electron as a particle and his son G.P. Thomson established it as a wave.

More recently the wave nature of a beam of electrons was demonstrated in a double slit experiment in 1989. In 1994 interference fringes were generated with beams of iodine.

We now take the wave nature of matter for granted. Diffraction of beams of electrons or neutrons are used routinely to study the atomic structures of solids and liquids.

One may wonder how to reconcile with the tracks of electrons - which are strings of bubbles left in the liquid hydrogen that fills the bubble chamber. Where is the wave? Explanation lies in thinking the bubbles that form the track as a series of detection points at which the matter wave undergoes constructive interference. For any other path matter waves cancel each other by destructive interference.

What quantity varies in a wave like fashion in matter waves? What equations does the amplitude of matter wave satisfy? Answers of such questions and many more were provided when Erwin Schrödinger proposed wave mechanics in 1926.

Schrödinger Equation:

Schrödinger proposed that the amplitude of matter wave associated with a particle of mass 'm' moving in the potential energy $V(\vec{r},t)$, $\Psi(x,y,z,t)$ called wavefunction satisfies the differential equation

$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\Psi + V(\vec{r},t)\Psi \text{ ------------------(1)}$$

It is called Schrödinger's time-dependent equation. For a free particle it reduces to

$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\Psi \text{ ---------------------------- (2)}$$

When potential energy does not depend on time, we can separate the space & time variables.

Writing $\Psi(\vec{r},t) = \phi(t)\psi(\vec{r})$ --------------------------(3)

We have

$$i\hbar\frac{1}{\phi(t)}\frac{\partial\phi(t)}{\partial t} = \frac{1}{\psi(\vec{r})}\left[-\frac{\hbar^2}{2m}\nabla^2 + V(\vec{r})\right]\psi(\vec{r}) = E \text{ (a constant)}$$

Thus, we have two separate equations

$$\frac{d\phi}{dt} = -\frac{iE}{\hbar}\phi \text{ ---------------------------------(4)}$$

and $\left[-\frac{\hbar^2}{2m}\nabla^2 + V(\vec{r})\right]\psi(\vec{r}) = E\psi(\vec{r})$ ---------------(5)

Equation (4) can be integrated to give

$$\phi(t) = \phi(0)e^{-\frac{iE\hbar t}{\hbar}} = constant \times e^{-i\omega t}$$

The constant E has dimensions of energy and represents the total energy. Equation (5) is known as time-independent Schrödinger equation.

Equation (3) can be written as

$$\Psi(\vec{r},t) = \psi(\vec{r})e^{-i\omega t}$$

Thus $\frac{\partial\Psi}{\partial t} = -i\omega\Psi$ and $\frac{\partial^2\Psi}{\partial t^2} = -\omega^2\Psi$

Substituting these in equation (2) we get

$$\nabla^2\Psi = -\frac{2m}{\hbar^2}\hbar\omega\Psi = -\frac{2m}{\hbar\omega}\omega^2\Psi = \frac{2m}{E}\frac{\partial^2\Psi}{\partial t^2}$$

$= \frac{1}{v^2}\frac{\partial^2\Psi}{\partial t^2}$; [For a free particle E= $\frac{1}{2}mv^2$]

This is the familiar wave equation. Thus Schrödinger equation is consistent with wave equation.

Properties of wave function:

1) The potential energy V is real, therefore for real Ψ right side of equation (1) would be real and left side complex. Therefore wavefunction Ψ is, in general, complex.
2) Being complex, the wavefunction itself does not represent a physical quantity.
   Max Born [8] suggested that $\Psi^*\Psi = |\Psi|^2$ be interpreted as probability density for finding a particle at position $\vec{r}$ at time t. That is, $|\Psi|^2 d\tau$ represents the probability of finding the particle in volume element $d\tau$ at position $\vec{r}$ at time t. Matter wave can then be regarded as probability wave.

   Multiplying equation (1) from left by Ψ^* and complex conjugate of equation (1) from right by Ψ and subtracting we get

   $$i\hbar\frac{\partial}{\partial t}(\Psi^*\Psi) + \frac{\hbar^2}{2m}\vec{\nabla}.[\Psi^*\nabla\Psi - (\nabla\Psi^*)\Psi] = 0$$

   Or $\frac{\partial}{\partial t}(\Psi^*\Psi) + \frac{\hbar}{2im}\vec{\nabla}.[\Psi^*\nabla\Psi - (\nabla\Psi^*)\Psi] = 0$

   With $P(\vec{r},t) = \Psi^*\Psi \Rightarrow$ probability density and $\vec{S}(\vec{r},t) = \frac{\hbar}{2im}[\Psi^*\nabla\Psi - (\nabla\Psi^*)\Psi] \Rightarrow$ probability current density the above equation becomes

   $$\frac{\partial P}{\partial t} + div\,\vec{S} = 0$$

   Which is the equation of continuity for probability wave.
   For a plane wave $\nabla\Psi = ik\omega$ and $\vec{S} = \frac{\hbar k}{m}\Psi^*\Psi = \vec{v}P(\vec{r},t)$.
3) Since $P(\vec{r},t)d\tau$ represents the probability of finding the system in volume element $d\tau$ at near position $\vec{r}$ at time t, $P(\vec{r},t)$ must be single valued and finite everywhere. Thus $\Psi(\vec{r},t)$ should be finite and single-valued everywhere. The wavefunction and its derivatives must also be continuous everywhere.
4) Since probability of finding the particle anywhere in the entire space must be unity,

We have

$$\int_V \Psi^*(\vec{r},t)\,\Psi(\vec{r},t)d\tau = 1$$

Where integration extends over all space.

Wavefunction satisfying the above condition is said to be normalized. The wavefunction can always be multiplied by a phase factor of unit magnitude without changing its physical significance.

A wavefunction satisfying the condition

$$\int_{r=0}^{\infty}\int_{\theta=0}^{\pi}\int_{\phi=0}^{2\pi}\Psi^*\,\Psi r^2 dr\, sin\theta d\theta\, d\phi = N$$

Where N is real and finite, is said to be normalizable in the sense that

$$\Psi_N = \frac{1}{\sqrt{N}}\Psi \text{ is normalized.}$$

Such functions are said to be square integrable. For this $\Psi(\vec{r})$ must tend to zero faster than $\frac{1}{r}$ as $r \to \infty$.

However, a plane wave which is an acceptable solution of Schrödinger equation for free particle (V=0 or constant) does not satisfy the above condition. Such wavefunctions have to be normalized in a different manner.

Two different methods have often been used for normalization of plane wave $e^{i(\vec{k}.\vec{r}-\omega t)}$

a) Box normalization: $\Psi_N(\vec{r},t) = \frac{1}{L^{3/2}} e^{i(\vec{k}.\vec{r}-\omega t)}$
b) Dirac delta function normalization: $\Psi_N(\vec{r},t) = \frac{1}{2\pi^{3/2}} e^{i(\vec{k}.\vec{r}-\omega t)}$

5) Schrödinger's equation is linear in Ψ, hence if Ψ_1 and Ψ_2 are two different solutions of the equation, any linear combination of these $\Psi = c_1\Psi_1 + c_2\Psi_2$ will also be a solution of Schrödinger's equation. This makes the superposition principle hold good. Interference and diffraction phenomena are its consequences.

Wave Packets

For a plane wave, the probability per unit volume $P(\vec{r},t)$ is the same everywhere at any time. Hence it cannot represent a localized particle for which $P(\vec{r},t)$ should be large in a limited space. A localized particle is represented by a wave packet which is a result of superposition of a group of waves having slightly different wavelengths centred around λ. Due to interference, the amplitude of the wave packet may be appreciable only in a limited region of space, giving greater probability of finding the particle in that region.

Matrix Mechanics

In 1925 Werner Heisenberg [9] in Gottingen discovered a new mathematical way of treating problems in atomic physics. It was called matrix mechanics because quantities which in Newtonian Mechanics are represented by ordinary numbers are represented in this theory by entities known as Hermitian matrices. This theory caused physicists a lot of trouble because of their unfamiliarity with matrix algebra. Erwin Schrödinger's wave mechanics came on the scene in 1926 to a great relief of the physicists. A few months later Schrödinger himself discovered and P.A.M. Dirac established that two theories were identically the same. They were merely dressed in different mathematical costumes that it took some time to recognize them. Now we consider these two different pictures of the quantum mechanics.

The discovery of quantum mechanics gave such a boost to theoretical physics that 1927 became the most fruitful year for theoretical physics. There was the development of quantum theory of radiation by Dirac. Dirac also developed relativistic quantum theory of electron which led to the prediction of the existence of antiparticles. Sommerfeld laid the foundations for the whole modern theory of metals and semiconductors by applying the quantum mechanical theory to free electrons in a conductor. Heitler and London applied quantum mechanics to the theory of covalent chemical bond between two hydrogen atoms. Heisenberg applied it to explain ferromagnetism.

It was indeed like a cloud burst in the field of theoretical physics. Heisenberg was awarded the Nobel Prize in 1932 for the development of quantum mechanics, and Schrödinger received it in 1933 for proposing a fertile new form of atomic theory.

Heisenberg's Uncertainty Principle

In 1927 Heisenberg proposed his uncertainty principle. It states that measured values cannot be assigned to the position $\vec{r}$ and momentum $\vec{p}$ of a particle simultaneously with unlimited precision. In fact, the uncertainty in the components of $\vec{r}$ and $\vec{p}$ are related as

$$\Delta x.\Delta p_x \geq \frac{\hbar}{2}$$
$$\Delta y.\Delta p_y \geq \frac{\hbar}{2}$$
$$\Delta z.\Delta p_z \geq \frac{\hbar}{2}$$

Even with the best measuring instruments that modern technology can provide, the product of uncertainties in the position and momentum components can never be less than ħ/2. The result is consistent with those obtained from the consideration of a wave packet. However, Heisenberg did not relish the idea of matter waves. He arrived at his conclusion through the method of matrices. More generally, any two canonically conjugate observables satisfy the uncertainty principle. For example:

$$\Delta E.\Delta t \geq \frac{\hbar}{2}, \text{ where E is energy and t is time.}$$

The probabilistic nature of results of measurements in quantum mechanics and uncertainty principle are intimately related. In fact, these are essence of quantum mechanics and are completely at variance with the absolute determinism of classical mechanics.

Quantum Weirdness

In quantum world particles display bizarre behaviours, that physicists, in desperation, call quantum weirdness. For example, a quantum particle can occupy more than one position or take more than one path at the same time. This simultaneous existence of different possibilities is known as coherent superposition or quantum coherence.

In classical physics observer could be kept separate from the observed. In quantum physical experiments an observer is capable of bringing about a particular outcome from the coexisting possibilities inherent in any quantum system. The quantum physicists have demonstrated beyond any reasonable doubt that 'observer' and 'observed' are fundamentally connected; their relationship is interactive and participatory.

Although several experiments demonstrate this relationship, one that reveals this most vividly is called the "entanglement" or "nonlocality" experiment. It is also known as EPR experiment, after the thought experiment proposed Einstein, Podolsky and Rosen [10] in 1935 to disprove quantum mechanics. This thought experiment predicted result so strange that Einstein rejected them concluding that it shows a deep flaw in quantum mechanics.

Suppose a source emits two photons simultaneously in opposite directions. Each photon has a certain property (say X) that may have two values (X_1 and X_2 say). (The property is actually polarization direction of the associated wave).

Because the two photons are generated simultaneously in a coordinated emission, it is always true that if photon A has value X_1, then photon B will have value X_2. These two photons taken together constitute a single system that can exist in two states, namely, (AX_1, BX_2) and (AX_2, BX_1). Before any measurement is made, quantum mechanics predicts that the actual state of this two-photon system is an intimate equal parts mixture of both states.

These experiments not only demonstrate the participatory relationship between the observer and observed, they have been utilized to achieve a form of "quantum teleportation" once thought to belong to science fiction. By superimposing some property of a third photon on one of the twins, the superimposed marker is also instantly teleported to the other twin, wherever it is. This has been done for entangled electrons as well.

2. Conclusion

This narrative review has retraced the milestones that shaped quantum mechanics, from Planck's early quantization hypothesis to the profound philosophical debates surrounding quantum entanglement. It highlights how the particle-wave duality, uncertainty principle, and quantum superposition not only redefined classical physics but also laid the groundwork for modern technologies. As quantum research advances into realms of computation and communication, revisiting these foundational breakthroughs remains vital for both educators and scholars.

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