Classical Physics versus Quantum Physics: An Overview

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Abstract

*Newtonian mechanics is the foundation of Classical Physics. Newton's mechanics, Thermodynamics, Wave theory of Optics and Maxwell's electromagnetic theory belong to regime of Classical Physics and can be used to explain a wide range of phenomena in the Universe at macroscopic scale. These theories fail spectacularly when applied to phenomena*in the atomic and nuclear regime, for example, *proton-atom scattering or the flow of electrons in a semiconductor.* Q*uantum mechanics is the most successful scientific theory that has ever been created and it has completely changed our view of the world. The failure of Classical Physics was highlighted by black body radiation and photoelectric effect. Max Planck and Albert Einstein provided explanations of both phenomena based on quantum hypothesis and are thus considered founders of Quantum Physics.*

The origin of quantum mechanics goes back to the mid-1920s.It was formulated first as matrix mechanics by Werner Heisenberg, Max Born and Pascual Jordan; then as wave mechanics by Louis de Broglie and Erwin Schrödinger; and later on asquantum statistics of subatomic particles by Fermi-Dirac and Bose-Einstein. Combining relativistic mechanics with quantum mechanics, Dirac formulated his relativistic quantum mechanics during 1930s. Uncertainty Principle is thecornerstone of Quantum Physics. The role of randomness in microscopic physical processes shatters the myth that the universe is deterministic. Quantum world is unpredictable in the classical sense and demolishes the idea of an objective universe. The Copenhagen interpretation remains the quantum mechanical formalism that is currently most widely accepted amongst physicists.Quantum theories support cosmic spirit pervading the cosmos and inter – relationship of individuals in the world society. Quantum philosophy is holistic and is going to revolutionize our world-view.

Keywords: *Natural Phenomena, Classical Physics, Quantum Physics, Determinism, Uncertainty Principle, Quantum Philosophy, Nature of Reality*

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INTRODUCTION

The principles of natural phenomena have been studied by Philosophers and Scientists both since the beginning of historical times. Prior to the 20th century, the dominant world view was based on Classical Physics which led to determinism, a tenet that had its origins in the philosophical thinking of Rene Descartes of France. Descartes considered the universe as a gigantic clockwork machine that moves relentlessly onward, towards eternity. According to its interpretation, the future is preordained and fully predictable. All of natural phenomena is described precisely by physical laws, and, in principle, can be predicted from past to future in the frame work of Classical Physics with precision.

In the first decades of the 20th century, Physicists and Philosophers had a big surprise in store as their world view was subverted, uprooted, and toppled by a physical theory called quantum mechanics. Classical Physics can explain a wide range of macroscopic phenomena, such as the motion of billiard balls andspace rockets, but they fail spectacularly when applied to microscopic phenomena, such as proton-atom scattering or the flow of electrons in a semiconductor. The world as it appears to our senses is not what it really is. Behind the apparent solidity of everyday objects lies an exotic shadow world of potentiality and uncertainty. This world, as we will see, defiessimple description since its foundations are so different from our everyday experience.

The transition from the microworldto the macroworld, i.e., how the macro world emerges from the microcworld, is an enigma for both Physicists and Philosophers. The theory that explains how the microworld works is called quantum mechanics. It is the most successful scientific theory that has ever been created and it has completely changed our view of the world. Yet, for all of its success, there are aspects of quantum theory that remain utterly baffling, even to physicists like Albert Einstein. Richard Feynman once said, "I think I can safely say that nobody understands quantum mechanics." According to Steven Weinberg, "There is now in my opinion no entirely satisfactory interpretation of quantum mechanics."

(a) Role of Classical Physics and Determinism

In classical physics, all properties of a particle or a system could be known to infinite precision. A classical physicist uses trajectories for measurement of position and momentum of a particle: $[\mathbf{r}(t), p(t); t > t_0]$, gives trajectory at time t, where the linear momentum is, by definition:

$$p(t) = m d/dt\,\mathbf{r}(t) = mv(t), \quad \text{m is mass of the particle.}$$

Trajectories are ‘state descriptors’ in Newtonian physics. Evolution of the state of a particle is represented by its trajectory. To know the trajectory for t>to, we need to know $V(\mathbf{r}, t)$, the potential energy of the particle and its initial conditions at t_o.

From Newton’s Second Law of motion: $m d^2/dt^2\mathbf{r}(t) = - V(\mathbf{r}, t)$

From initial conditions, we can predict position and momenta of all particles – indeed, of the entire universe. Hence classical physics ascribes to the universe an objective reality, an existence external to and independent of human observers. The nature of classical universe is that it is predictable and it led to notion of determinism, which supported by Newtonian mechanics and French philosophers (Descartes et al.) dominated philosophical thinking until the advent of quantum theory.

If the universe is determinate, then for every effect there must be a cause. Principle of causality was a rock on which the structure of classical physics was raised during 19th century. It predicts reproducibility of experimental results. Universe behaves as a vast, mindless machine and the Free Will has no role to play. In this universe, our loves, hopes, and dreams are mere delusions and human aspirationsare pointless. It is akin to Karma theory of Hinduism; every event predetermined and pre-destined. The determinism is a dehumanizing philosophy. It led to rise of Marxism in Europe. Determinism is boring. It is also wrong.

FAILURE OF CLASSICAL PHYSICS

(a) Black Body Radiation: Classical Physics failed to explain Black Body spectrum of radiation over all frequency ranges, which came to be known as UV catastrophe. There was an in-congruency between theory and experiment. Classically, the radiant energy density $d\rho$ was described by the following equation:

$$d\rho(\nu,T)=8\pi\kappa_B T\nu^2 d\nu/c^3$$

The above formulation proves that as the frequency of light ν increases the radiant energy density approaches infinity as shown in Figure 1. However, the experimental results contradict the theory. In fact, it was established by experiments that the radiant energy density tends to decrease as the frequency increased in the UV spectrum.

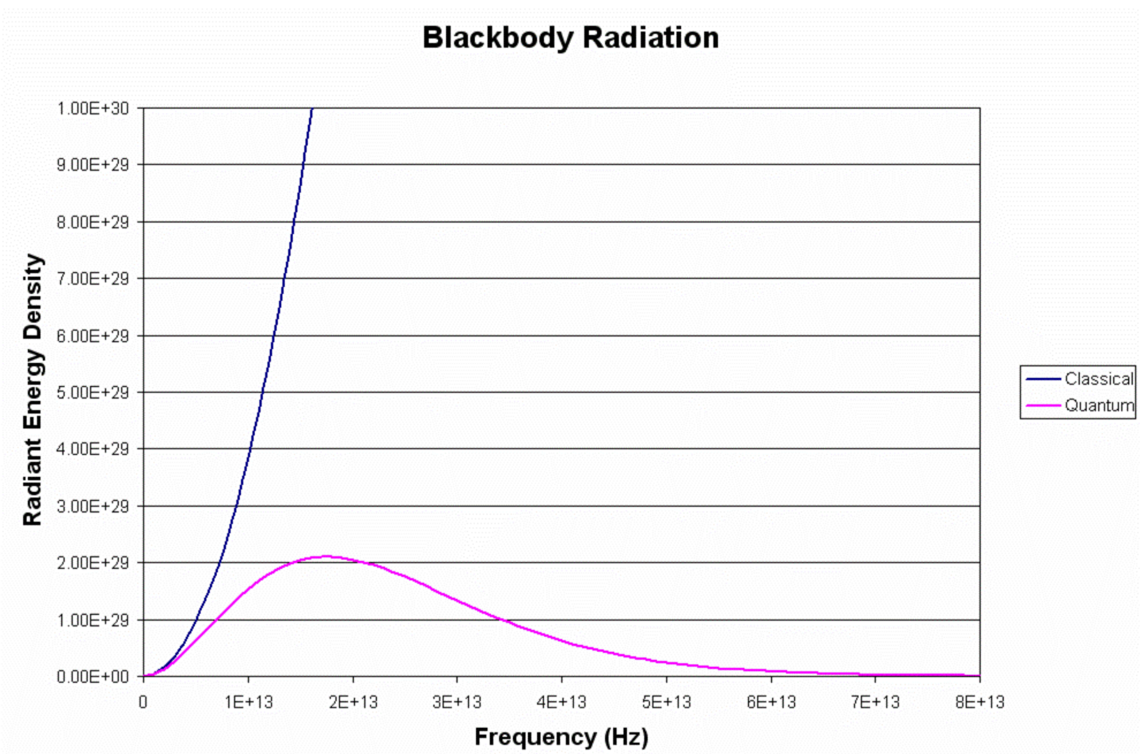

Fig. 1: A comparison of the classical and the quantum models of blackbody radiation. The quantum model explains experimental values at all ranges of frequencies whereas the classical model fails at high frequencies. Classical model and quantum models agree at low frequencies.

Max Planck (1900) successfully explained blackbody radiation and derived the following equation to accurately describe the experimental results (refer to Figure 1):

$$d\rho(\nu,T)=8\pi h/c^3\ (\nu^3 d\nu/e^{h\nu/\kappa_B T}-1)$$

Planck was able to derive this formula by assuming that the energies of the oscillators were quantized (i.e. $E=nh\nu$, where h is Planck's constant = $6.626x10^{-34}$J-s. Planck's quantization of energy was a revolutionary assumption that marked the beginning of a new field of Quantum Physics.

(b) Photoelectric Effect: Quantum Physics approach was used to explain the experimental results of the photoelectric effect, which is simply ejection of electrons from a metal surface when light beam falls on it. Classical physics describes light as a wave with a set frequency and amplitude where the amplitude is related to the intensity. The classical explanation was that the metal's electrons would oscillate with the light and eventually break away from the surface with a kinetic energy that would depend on the intensity of the incident radiation. However, the experimental observations show that the kinetic energy of the ejected electrons is independent of the intensity of the radiation. In fact, no electrons were ejected,no matter how intense the incident radiation was, if frequency of light beam is lower than a given threshold frequency for that metal.

Planck's concept of quantized energy was used by Einstein in a modified form to describe the experimental results of Photoelectric effect. Einstein proposed that light could travel in small quantized packets of energy (photons) instead of strictly behaving as a classical wave. Einstein showed that the kinetic energy of the ejected electrons was equal to the energy of the incident photon minus the energy barrier (known as work function □) to releasing an electron from that particular metal. This interpretation is described by the following equation:

$$KE=1/2\ mv^2 = h\nu - \square$$

Thus Einstein model was able to fully account for the experimental results including the lack of dependence of the energy of the ejected photons on the intensity of the incident radiation.The failure of some frequencies of light to eject any photons from the metal surface is based on the fact that the incident photons have energy less than the work function of the metal.

Photoelectric effect was used by Einstein to experimentally determine the value of Planck constant$h$, whichproved to be the same as determined by Planck. This gave credence to the idea of quantized energy and Quantum Physics as a whole, which was still viewed with suspicion by many scientists including Einstein.

(b) THE QUANTUM POINT OF VIEW

In quantum world-view, we must abandon the classical notion of a particle and its trajectory. At microsopic level, an electron behaves as a particle and as a wave (dual nature of matter). Hence, its trajectory is unpredictable and concept of determinism is no longer valid in quantum world. Quantum behaviour can be expressed in the language of probabilities, not certainties. It is inherently statistical in nature and involves random chance. Heisenberg’s principle is the rock stone of quantum world:

$$\Delta x\ (t_o)\ \Delta p_x\ (t_o) \geq 1/2\ h/2\pi \geq 1/2\ \hbar,$$ where h (Planck’s constant) = $6.626x10^{-34}$J-s.

In the microworld of atoms and nuclei, experimentation fails in discovering the nature of reality but rather it is a way of creating certain aspects of reality. An observer cannot observe a microscopic system without altering some of its properties. The observer-observed interaction cannot be reduced to zero, in principle.Quantum world is unpredictable in the classical sense, as randomness rules the roost, and it demolishes the idea of an objective universe. The philosophy of determinism is given its burial in Quantum world.

Position and momentum are fundamentally incompatible observables, in the sense that precise value of one precludes knowing anything about the other. It is implicit in nature, that the universe is inherently uncertain. It is not the failure of experimental technique but a fundamental limitation on our knowledge of reality.

The demise of classical physics occurred around 1930 and thus began the quantum revolution in the world of phenomena. The particles do not have trajectories in the quantum world view. Bohr tried to reconcile the situation between the classical and quantum world by his Correspondence Principle. Classical physics provides precise informationabout the properties and behaviour of particles and systems but quantum physics says that it is not so because of constraints such as Heisenberg's Uncertainty Principle, which imposes a fundamental limit on knowledge.

(c) THE RISE OF QUANTUM PHYSICS

There are three stages in the development of Quantum Physics: (i) Planck's introduction of Quantum hypothesis or what is known as quantization of energy ($E=h\nu$). (ii) Bohr's old Quantum Theory, which served as a bridge between Planck's Quantum hypothesis and modern Quantum mechanics. (iii) Quantum theory of Heisenberg and Schrodinger. Though their versions look different (Matrix Mechanics and Wave Mechanics)but there is concurrence between the two approaches.

Neils Bohr took a clue from Planck's quantization hypothesis and introduced the idea of quantization of angular momentum of electrons in their orbits around the nucleus. Bohr's quantum theory served its limited purpose in atomic spectroscopy. It failed to explain even spectra of hydrogen atom successfully. Bohr's atomic model was improved by Sommerfeld. The Bohr-Sommerfeldquantization theory was able to explain many things about atomic spectra, including the fine structure of the hydrogen atom. In any case it remained as a model, and the real explanation of atomic spectra had to wait for the full quantum theory.

The atomic theoryof Bohr and the corpuscular theory of lightdeveloped by Einstein first came to be widely accepted as scientific fact and these theories can be viewed as quantum theories of matter and electromagnetic radiation, respectively. The origin of quantum mechanics goes back to the mid-1920s. It was formulated first as matrix mechanics by Werner Heisenberg, Max Born and Pascual Jordan; then as wave mechanics by Louis de Broglie and Erwin Schrödinger; and later on as quantum statistics of subatomic particles by Fermi-Dirac and Bose-Einstein. Combining relativistic mechanics with quantum mechanics, Dirac formulated his relativistic quantum mechanics during 1930s. The Solvay Congress of 1927 held at Brussels in Belgium started a debate on validity of Quantum Mechanics between Albert Einstein and Neils Bohr. This debate raised some acrimony between two giants but it ultimately led to the Copenhagen interpretation of Quantum Mechanics by Niels Bohr, which became widely accepted.

This historical photograph shows most of the Founders of Quantum Physics in 1927 Solvay Congress held in Belgium.

By 1930s, quantum mechanics was accepted as an ultimate theory of matter and radiation in the microworld. A greater emphasis was placed on measurement in quantum mechanics, the statistical nature of our knowledge of reality, and philosophical speculation about the role of the observer in later years. Quantum mechanics has since permeated throughout many aspects of 20th-century physics and other disciplines including quantum chemistry, quantum electronics, quantum optics, and quantum information science. Much of the Classical mechanics has been re-evaluated as the "classical limit" of quantum mechanics on the basis of Bohr's Correspondence Principle. More advanced developments have been realized in this field in terms of quantum field theory, string theory, and speculative quantum gravity theories.

COPENHAGEN INTERPRETATION OF QUANTUM PHYSICS

The Copenhagen interpretation - due largely to the Danish theoretical physicist Niels Bohr - remains the quantum mechanical formalism that is currently most widely accepted amongst physicists, some 75 years after its enunciation. According to this interpretation, the probabilistic nature of quantum mechanics is not a *temporary* feature which will eventually be replaced by a deterministic theory, but instead must be considered a *final* renunciation of the classical idea of "causality". It is also believed therein that any well-defined application of the quantum mechanical formalism must always make reference to the experimental arrangement, due to the complementarity nature of evidence obtained under different experimental situations.

Albert Einstein, himself one of the founders of quantum theory, disliked this loss of determinism in measurement. Einstein held that there should be a local hidden variable theory underlying quantum mechanics and, consequently, that the present theory was incomplete. He produced a series of objections to the theory, the most famous of which has become known as the Einstein–Podolsky–Rosen (EPR) paradox. John Bell showed that this "EPR" paradox led to experimentally testable differences between quantum mechanics and local realistic theories. Experiments have been performed confirming the accuracy of quantum mechanics, thereby demonstrating that the physical world cannot be described by any local realistic theory. The *Bohr-Einstein debates* provide a vibrant critique of the Copenhagen Interpretation from an epistemological point of view.

INTER-RELATIONSHIP BETWEEN CLASSICAL AND QUANTUM PHENOMENA

Predictions of quantum mechanics have been verified experimentally to an extremely high degree of accuracy. According to the correspondence principle between classical and quantum mechanics, all objects obey the laws of quantum mechanics, and classical m echanics is just an approximation for large systems of objects (or a statistical quantum mechanics of a large collection of particles). The laws of classical mechanics thus follow from the laws of quantum mechanics as a statistical average at the limit of large systems or large quantum numbers.

Classical mechanics accurately describes most systems that can be easily observed. Objects that are a "normal" size (larger than a molecule and smaller than a planet), at a "normal" temperature (anywhere close to room temperature), going at a normal speed (0 m/s- anything significantlyless than the speed of light) fit the models set forth in classical physics. It is only when the system being observed begins to violate these parameters that quantum factors come into play. An important aspect of the quantum mechanical models is the fact that as the conditions approach "normal" the quantum mechanical model approaches the classical model.

Quantum Mechanics (QM) approaches Classical Mechanics (CM) when:

- $\nu \rightarrow 0$, this is observed in the phenomenon of blackbody radiation (Fig. 1).
- $h \rightarrow 0$, this is observed when taking the limit as $h \rightarrow 0$ for the average quantum mechanical energy ($h\nu/e^{h\nu/\kappa_B T} - 1$). Notice that this limit is equal to the average classical energy ($k_B T$).
- $n \rightarrow \infty$, this is known as the Bohr Correspondence Principle (QM→CM, n→infinity).

Difficulties to Learn Quantum Physics

(i) We live in a macroscopic world and our common sense experiences and intuition pertain to it. Quantum physics is an affront to that intuition.

(ii) Quantum physics operates at a level that is one step removed from reality. In classical physics, we can visualize the phenomenon-particle trajectory, but in quantum physics, we wander through a haze of uncertainty, probability and indeterminacy. The microcosm can be understood but it cannot be seen.

(iii) Mathematics is the language of quantum physics. In classical physics, we use mathematics but we can discuss those ideas without recourse to mathematics. This is not possible with quantum mechanics. It is obligatory to think in a new, abstract mathematical way, not an easy task!

(d)PHILOSOPHICAL IMPLICATIONS OF QUANTUM THEORY

For more than 2000 years, Aristotlean view prevailed in science and it was believed that there are two sets of laws: One for the terrestrial sphere (earth) and the other for the celestial sphere, e.g., the sun and other planets. It was Newton who demolished Aristotlean concepts of physics by formulating his universal law of gravitation which holds its sway in both the spheres. In fact, most of the laws of physics are universal and must be Lorentz invariant.

Newtonian world – view was mechanical in nature and it gave rise to philosophy of determinism propagated by the French philosopher Rene Descartes. The Newtonian – Cartesian notions created the mind – body dichotomy as well as the dichotomy between the subject and object, values and facts, feeling and thought, poetry and prose and science and non – science. The methods of Newton and Descartes have made tremendous contribution for the development of science and technology and its attendant economic affluence. The mechanistic model of Newton and the reductionist approach of Descartes had influenced the western mind so much that the model extended also to social science and human behaviour. John Locke developed an atomistic view of the society by reducing the patterns of social behaviour to individual behaviour. Application of Locke's philosophy resulted in the development of a socio – economic system based on individualism, property rights, and free market economy. The philosophical basis for a capitalist society was thus provided by scientific rationalism and materialism. Globalisation based on the model of free economy has further accentuated the fragmentation of human society.

Fortunately, the quantum theory has rejected the world - view based on the Newtonian – Cartesian system and a 'holistic' approach may emerge in future to have a paradigm shift in the world – view. Unification ideas in science and society will replace the atomistic/reductionist world - view which fragmented the human race. Quantum theories support cosmic spirit pervading the cosmos and inter – relationship of individuals in the world society. Let us hope the religions of the world play a positive role for establishing world peace through inter – faith dialogue and science – religion dialogue, which is the need of the hour.

(e) SOME PHILOSOPHICAL QUESTIONS RELATED TO QM

Despite the fact that many predictions of QM have been verified experimentally, there are deep philosophical questions related to QM, especially with probabilistic/Copenhagen interpretation, for example: (1) How come that a cat in the black box can be in a state of half life and half dead if nobody observes it? (This is known as Schrödinger's cat paradox). (2) What is the exact mechanism of wavefunction collapse? (3) How can mind influence matter and observation according to Copenhagen view? (This is known as mind-matter interaction problem). (4) Is it true that according to Copenhagen view the moon will not be there if nobody observes it? Similarly if nobody looks at the sun, then the sun will disappear. How can it be? Some of these questions have baffled even greatest physicists since the beginning of QM theories. Historically, Einstein along with Schrödinger and De Broglie did not accept the probabilistic view of QM, while Max Born along with Dirac and Bohr prefered the probabilisic view. These questions are good to ponder especially if you would like to pursue a career in physics. It is true that those deep philosophical questions remain the subject of hot debates by many physicists until today.

One approach to solve the above baffling questions is to find correspondence between Quantum Mechanics and Classical Physics, with a purpose not just to find analogy between the two great ideas, but to find formal correspondence. We can mention a few among those efforts here: (1) It is found since long time ago, that there exists formal correspondence between Poisson bracket and commutator bracket in QM; (2) some experiments try to find connection between Quantum Physics and acoustics, since the wave mechanics can be related to classical wave equation; (3) some physicists are able to derive Planck's blackbody spectrum from zero point radiation and Classical Physics (cf. Timothy Boyer, http://arxiv.org/abs/1107.3446). Even recently there are a few physicists who made an attempt to derive the Planck law E=n.h.f from classical wave equation as starting point (cf. George Shpenkov and Xin-an Zhang). It is worthwhile to emphasize here that perhaps in the future we shall find a better understanding of the connection between QM and CM, or even perhaps a generalized theory unifying Quantum Mechanics and Classical Physics. To find a correspondence between QM and Classical Physics would be a good topic to ponder over for young scientists.

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