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"A Brief Breakdown of Quantum Physics "

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Abstract

My intent in this article, and a series of follow-on articles is to provide conceptual understanding or refresher mini-course related to quantum physics with a grain of critical review. Physics can be broken down into three main categories. Classical physics is the study of visible objects moving at speeds much less than the speed of light. Newtionian mechanics is a good example. Relativistic physics involves objects moving near the speed of light. Quantum physics, the focus of this article, deals with subatomic objects that cannot be observed directly and behave in a discrete, non-intuitive fashion. It is important to remember that the intent of physics should be the unbiased pursuit of understanding related to physical mechanisms behind the phenomenon being studied. Hypotheses are made and tested by experiments. If the results align with predictions over a series of experiments, then the status of the hypothesis is raised to that of a theory. If the theory holds true over a number of years, it is then elevated to a "law". Yet in all this process, little or nothing is known as to what causes the physical effect. We only have a set of tools to predict the outcome. This is of some value but when the results do not agree, unfortunately in modern physics, especially, rather than discarding the hypothesis, it is simply made more complex and/or "fudge factors" are added to the equations. In the end, either way, the physical mechanism typically remains unknown or highly ambiguous.

Key Quantum Physics Premises

There are five major premises, or principles. These are the basic foundations that drive hypotheses, experiments, theories, and laws involving quantum physics.

First there is the *uncertainty principle*, specifically known as the Heisenberg uncertainty principle. It states that one cannot precisely and simultaneously measure the position and momentum of an object. The product of the position uncertainty and momentum uncertainty is so small ($\frac{h}{4\pi}$) that it is barely observable in a classical application such as a bowling ball but is highly observable on the atomic scale such as for an electron. If the position of an electron is fully known, the uncertainty related to its momentum is infinite and vice versa.

A second quantum physics principle is one that directly relates to atomic energy states. As electrons orbit the nucleus of an atom, they do so only at *discrete levels* and can only change levels by either absorbing a photon (going to a higher level or breaking free from the atom) or by emitting a photon (dropping to a lower level). Such behaviour is in contrast to classical physics. For example, the kinetic energy of a baseball after it is released from a pitcher can take on almost an infinite number of possible energy states, within the constraints of factors such as the forces on the ball (e.g., pitcher's thrust, spin, wind, drag). I included the word "almost" here due to the Heisenberg uncertainty principle.

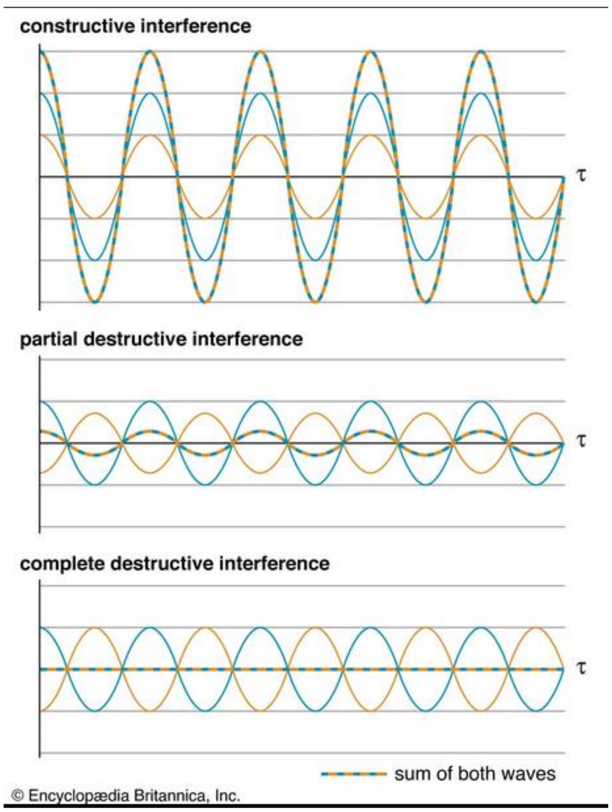

Figure 1 Waves combine by superposition to form a resultant wave that could have larger amplitudes, smaller amplitudes, or no amplitude.

A third key principle in quantum physics is that of *superposition*. It can be described as the result of simultaneously combining multiple possible states of an object. This is illustrated in Figure 1 from [1]. When amplitudes of separate, but locally resident, waves are combined simply by addition the result, colored in black, is the superposition of the red and blue waves.

One quantum physics principle that has been puzzling for decades is that of *wave/particle duality* which has been observed both in the propagation of light and in atomic particles such as electrons. Wave characteristics have been observed in the laboratory by directing a beam of coherent light through narrow slits as illustrated in Figure 2. After passing through the slits the light traverses to a flat screen where the incident light forms a well-structured pattern which is obviously due to superpostion of multiple waves emanating from the slits. Where the waves constructively interfere, as illustrated in the top graph of Figure 1, there are bright spots on the screen and where the waves destructively interfere, as shown in the lower graph, there is no illumination on the screen. Such behaviour strongly confirms the wave nature of light. This has also been done with particles, showing they have a wave nature as well (the deBroglie wavelength).

Other experiments have shown that light can also be modeled as particles. Einstein received a Nobel Prize for his research in the discovery of the photoelectric effect. He declared that when light is radiated on a metal surface (as shown in Figure 3), electrons are ejected with the sum of their exiting kinetic energy and binding energy equivalent to the energy of incident light packets, called photons. The reverse effect is also true. When an electron strikes a photosensitive material, photons are emitted. This principle the key technology applied in 20th century televisions that included cathode ray tubes.

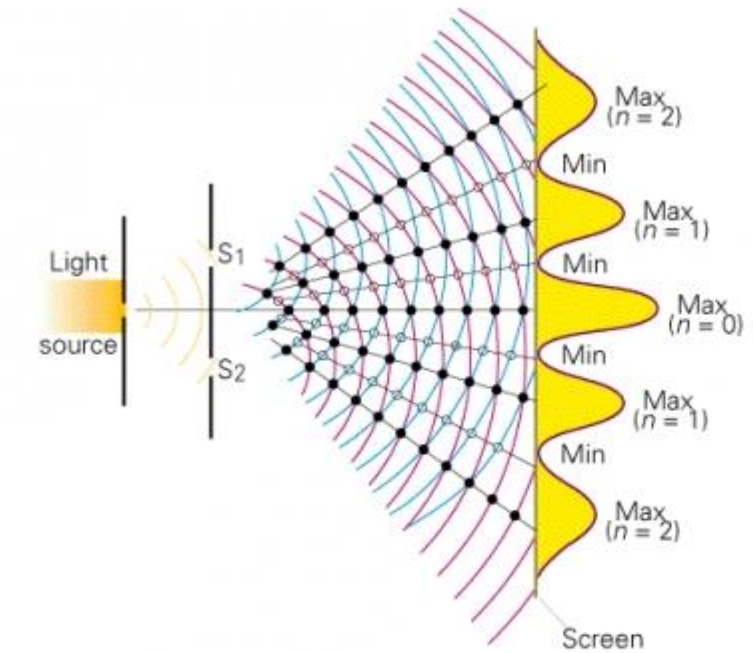

Figure 2 Double slit interference pattern demonstrating the wave nature of light [2].

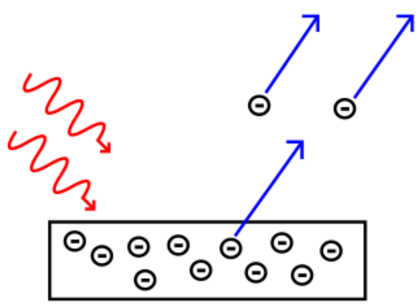

Figure 3 In the photoelectric effect, light packets, known as photons strike a metal surface, imparting their energy to electrons, setting them free from the bonds that hold them to the structure [image from Wikimedia Commons].

A final quantum physics principle introduced briefly here is called *quantum entanglement*. Einstein referred to this phenomenon as "spooky" action at a distance. Although highly abstract, and still not totally understood, entanglement is basically a situation in which two or more particles are coupled such that the state of one depends on the state of the other, regardless of the distance between them. Highly sophisticated experiments have been performed by such physicists as John Stewart Bell in 1964. He demonstrated that there is correlation between state changes between entangled pairs of electrons [3]. Several similar experiments followed and in 2016, Fang-Fang Du, et. al., revealed quantum entanglement of electron-positron pairs by measuring and analyzing the emitted photons from their annihilation events [4]. More will be included on this topic in following articles in my quantum physics series..

Various Domains Within Quantum Physics

There are many elements of study belonging to the umbrella of quantum physics. Most of which are included in the Venn diagram provided in Figure 4. Brief paragraphs are provided herein to introduce each element. These areas of physics, supported by the establishment of mathematical tools and complex experimental equipment such as the Large Hadron Collider (LHC) where extremely high energy magnetic fields are used to propel subatomic particles at speeds near the speed of light.

There are only subtle differences between *quantum physics* and *quantum mechanics* with the latter being an extention of the former through the establishment of of mathematical rules that govern the behavior of subatomic particles. The behavior of subatomic particles is stikingly different from that of objects as described by classical physics. When Niels Bohr developed his model of the atom with electrons oribiting around the nucleus as planets orbit the sun, an important issue was raised. Since an electron is a charged particle and the rotational orbital trajectoy involves acceleration, according to Maxwells laws of electromagnetism, the electron would be radiating electromagnetic energy and this would result in losing kinetic energy and eventual coliding with the nucleus. Around that time Max Planck, established the theory that the electrons must have discrete number of wavelengths in one full cycle. This was corroborated by De Broglie, who gave rise to the notion that, since light must have a dual nature (both wave and particle), then particles may also have a wave nature, an hypothesis was verified through well established experiments. Such wave nature was soon codified by Erwin Schrodinger in his famous Schrodinger Wave Equation, the cornerstone of quantum mechanics.

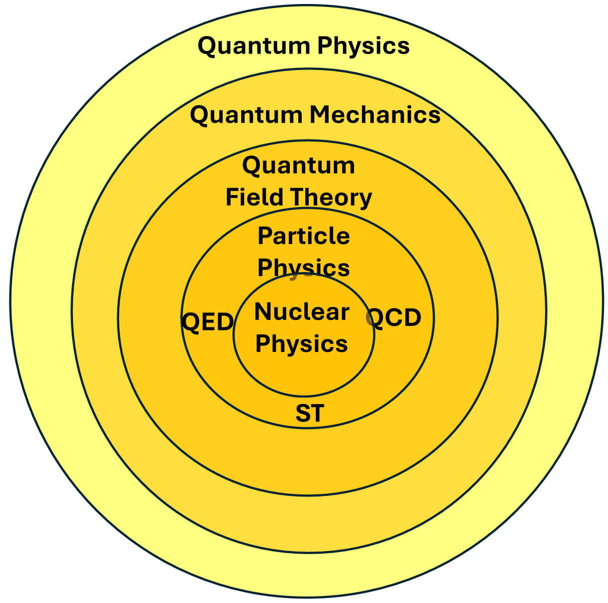

Figure 4 Venn diagram of the components of quantum physics

In the simplest form, *quantum field theory* can be described as a mathematical framework whereby the interactive behavior of quantum particles, such as electrons and photons (there are many others according to the standard theory) can be accurately predicted. This field of study has emerged from the combination of quantum mechanics with special relativity but has not been found to be compatible with the theory of general relativity.

Nuclear physics emerged as a field of study at the end of the 19th century with discovery of radioactivity by Henri Becquerel. The focus of this research area is on the core of the atom, i.e., the nucleus which consists of protons and neutrons (hadrons). It is the quantitative combination of these hadrons that determine the distinct characteristics of the atom to which the nucleus belongs, with their sum being the atomic mass and the number of protons beint the atomic number. Since the 1970's, other discoveries have been made that serve to answer the question "how can the nucleus hold together when it is composed of particles that are either neutral or the same charge. Then came quarks to hold the hadrons together and gluons to hold the quarks together.

Nuclear physics has provided us with such things as nuclear energy, radiometric dating, and nuclear weapons. Since the 1970's it has been expanded to a new field of research we call *particle* *physics*. Theoretical and experimental particle physicists alike have used complex mathematical equations, some of which I will include in future articles, and massive particle accelerators to predict and hopefully observe such exotic particles as the Higgs boson, quarks, and gluons. The standard model for quantum particles is shown in Figure 8. Notice the resemblance to the periodic chart for elements.

Quantum electodynamics (QED) is an area of study in which a series of interactions involving electrons, positrons (anti-electrons), and photons can be predicted. Key physicists such Richard Feynman and Freeman Dyson developed graphical (Feynman diagrams) and codified the physics into equations (Dyson) [5]. A link in a chain reaction can be described by Feynman diagrams as the one shown in Figure 5, where a photon yields its energy to form an electron/positron pair. The positron is the anti-matter version of an electron. It contains a positive charge that balances with the electron so charge is conserved. The kinetic energy of the resultant particles is dependent on the energy of the photon that produced them such that energy and momentum are conserved. The strength, or likelihood of the reaction is represented by the value, Q_e. When this approach to predicting reactions between other other particles such as quarks and gluons, the assocated research area is called quantum chromodynamics, or QCD. As shown in Figure 6, a quark/anti-quark pair combine to form a transitory gluon that almost immediately yields its enegy to form a new quark/anti-quark pair with the reaction strengths designated by the quantities $\sqrt{\alpha_s}$.

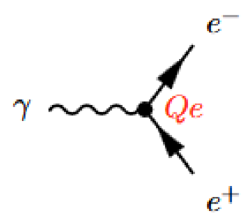

Figure 5 A simple example of a Feynman diagram showing a photon transitioning to an electron/positron pair. Qe is a coefficient representing the strength of the reaction.

There remains, however, an ongoing problem within physics and that is at the intersection between relativistic and quantum physics. Unfortunately, these major areas of physics have not yet been reconciled into a unified field theory. A striking example of this is gravity, a phenomenon that appears to be mathematically predictable with precision but not yet fully understood physically (some believe gravity waves do this but the jury is still out). This has given rise to a hypothesis that there could be a binding type particle, specifically a boson (e.g., photon, gluon), that provides a gravitionally attractive interaction (a graviton) between objects based on mass, as there is on objects based on electric charge or magnetic dipoles. Research in this area has led to field in the late 20th century, known as *string theory* (ST) [6]. What this research has culminated into, however, is a ten dimensional universe, requiring six new unobservable dimensions. Although this hypothesis might have mathematical merit, it is unfalsifiable because it would require oreders of magnitude more energy than what is even available at the LHC.

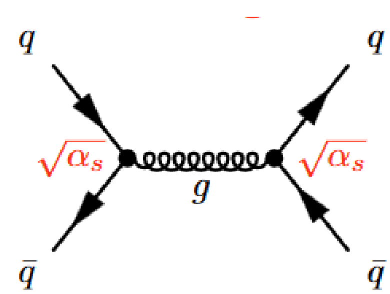

Figure 6 A Feynman diagram showing a strong connection between quarks and anti-quarks via a gluon.

Final Discussion

In this brief article, I have provided a high level overview of quantum physics with all of its major parts and extensions. Most of what I have covered Is within the realms of what is accepted within the modern physics establishment. Much of the widely accepted laws of quantum physics have been well laid out by highly intelligent mathematicians and physicists. As mentioned earlier, there will be a follow on series of introdutory articles I plan to write that will focus on each area alluded to here.

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