Quantum Mechanics

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Quantum mechanics (QM) is the modern physical theory of very small (microscopic) systems, typically atomic-sized or smaller. Along with Einstein's theory of relativity, QM represented a major revolution in our understanding of physics, which was previously described by Newtonian (classical) mechanics.

History of QM [1]

Problems with Classical Physics

The enormous success of Newtonian mechanics led Lord Kelvin to state the following in 1894 [2]:"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement." How wrong he was! However, it seemed that way for many physicists at the end of the 19th century.

Nevertheless, there were several unexplained problems with classical physics at this time, most notably the blackbody radiation problem, the photoelectric effect, and the existence of spectral lines.

The Blackbody Radiation Problem

A *blackbody* is a theoretical substance that absorbs all radiation incident on it. Many physical systems are very good approximations to blackbodies, for instance, stars and boxes with a tiny hole. Gustav Kirchoff first discussed the blackbody radiation problem in 1859. The problem is that according to classical physics, a blackbody should radiate more and more energy at higher and higher frequencies (shorter and shorter wavelengths), and should thus radiate an infinite amount of energy. Since this obviously does not happen, an explanation was required. Max Planck solved the blackbody radiation problem by postulating that radiation was not continuous but discrete, coming in lumps known as *quanta*. The energy E of a quantum of radiation is given by the formula $E = hf$, where f is the frequency of the radiation and h is a fundamental constant, which became known as *Planck's constant*. Planck's formula leads to the correct prediction of the blackbody spectrum. The value of Planck's constant is tiny; it is approximately equal to 6.6×10^{-34} Joule-seconds. This is why quantum mechanics is not apparent in everyday life.

The Photoelectric Effect

The *photoelectric effect*, discovered by Heinrich Hertz in 1887, is the phenomenon by which electrons are ejected from the surface of a metal when light of sufficiently high frequency is shone on it. The problem with this effect was that classical physics did not predict what was observed. According to classical physics, the rate at which electrons are ejected should only depend on the intensity of the light, not on the frequency. However, it was observed that no electrons are ejected if the frequency of the light is below a threshold frequency. Albert Einstein explained this effect in 1905 by postulating the existence of *photons*, particles of light, each with energies given by Planck's formula. (Amazingly, it was for this discovery, not for the theory of relativity, that Einstein was awarded the Nobel Prize in 1921.) Although Einstein had correctly explained the photoelectric effect, he left us with the seeming paradox of the dual wave-particle nature of light.

The Hydrogen Spectrum

Classical physics could not explain the existence of discrete lines in the emission spectrum of all substances, hydrogen in particular. Shortly after Rutherford's development of the atomic theory, it was noted that this theory was in serious trouble. Since it was well-known that charged particles radiate energy, according to his model, the electron orbiting the proton in a hydrogen atom should very quickly (in the order of a millionth of a second) radiate away all of its kinetic energy and fall into the proton. Since this obviously does not happen, an explanation was required. In 1913, Neils Bohr offered an explanation. According to Bohr, the energy of an electron in a hydrogen atom is not continuous but discrete, so when it radiates energy, it does so in discrete "jumps", emitting photons with a discrete set of energies in the process. He was able to predict these energies, which precisely matched the observed energies of the hydrogen spectrum. Moreover, Bohr's model involves a ground state for hydrogen, in which the electron is forbidden to decay any further. Thus, Bohr solved both the problem of the hydrogen spectrum and the problem of the stability of hydrogen.

Development of QM

With these early developments, QM quickly developed over the next several years, culminating with a full-blown theory developed independently by Werner Heisenberg and Erwin Schrodinger from 1925 to 1927. For awhile, these seemed to be rival theories, and indeed their styles are very different, although in 1927, Schrodinger showed that both theories are equivalent, i.e., they make exactly the same predictions.

Matter Waves

Inspired by the success of the wave-particle dual nature of light, in 1923, Louis de Broglie hypothesized that like light, particles of matter, such as electrons and protons, exhibit wave properties as well. He was also able to predict the wavelength of these matter waves. In 1927, Clinton Davisson and Lester Germer demonstrated the wave nature of the electron in their electron diffraction experiment, and they showed that de Broglie had predicted the correct wavelength of these waves.

Heisenberg’s Formulation of QM

In 1925, Heisenberg devised a theory of QM, which at the time was known as *matrix mechanics*. According to this theory, all observable quantities of particles, such as energy and momentum, are described by matrices rather than single numbers.

Schrodinger’s Formulation

In 1926, Schrodinger devised another formulation of QM (later shown to be equivalent to Heisenberg’s formulation), which became known at the time as *wave mechanics*. He elaborated on de Broglie’s theory of matter waves, precisely describing their wave behavior (as well as that of light) with a *wavefunction*.

Consequences of QM

QM has some very puzzling consequences, which defy intuition. As a result, Neils Bohr declared, “Those who are not shocked when they first come across quantum theory cannot possibly have understood it.” [3]

Wave-Particle Duality

As we have seen, according to QM, everything has both wave and particle properties. Moreover, according to Bohr’s *compelementarity principle*, both of these descriptions are required, but they cannot both be observed simultaneously. Instead, which property is observed depends on the experimental apparatus devised to observe them. For instance, the double slit experiment is devised to detect the wave nature of light (or electrons), but if we try to detect which slit a photon or electron goes through, we destroy the resulting interference pattern once we detect it as a particle.

The Uncertainty Principle

Heisenberg formulated this principle in 1927, which states that two complementary observable quantities, position and momentum, for instance, cannot both simultaneously be measured to arbitrary precision. Instead, the product of the uncertainities of each of these quantities cannot roughly exceed Planck’s constant.

Here’s a way to understand the uncertainty principle. Suppose we wish to simultaneously measure both the position and the momentum of an electron. We can imagine observing it with a very powerful microscope. By using light of a very short wavelength, we may be able to precisely pin down the position of the electron. However, in so doing, we give the electron a big kick, due to the high momentum of the photon in accordance with Planck’s law. Thus, our uncertainty of the momentum of the electron is large. Conversely, if we wish to more accurately determine its momentum, we may employ low energy photons, but these have long wavelengths, jeopardizing the accuracy of our measurement of the position of the electron.

Einstein was unhappy with the uncertainty principle (and with QM in general, although ironically, he was one of its pioneers!) During the 1930s, he devised several thought experiments designed to disprove the uncertainty principle, but Neils Bohr was able to find a flaw with each of them. One of Einstein's thought experiments led Bohr to lose a night's sleep, but by the next day, he devised a counterargument which ironically used many of Einstein's ideas from general relativity.

Probability

Probability plays a fundamental role in QM. Max Born interpreted the square of the absolute value of the wavefunction as the probability of finding a particle in a given place at a given time. This probability is not a reflection of our ignorance, but is a fundamental property of QM. Einstein was very unhappy with this interpretation, leading him to declare, "God does not play dice." Bohr rebutted, "Stop telling God what to do!" Einstein tried to explain away these probabilities by postulating the existence of *hidden variables* [5]. In 1964, John Bell showed that experiments could be devised to test whether these hidden variables exist, and in the early 1980s, Alain Aspect demonstrated that these hidden variables do not exist [6].

EPR Paradox [7]

In 1935, Albert Einstein, Boris Podolsky, and Nathan Rosen (collectively known as EPR) devised a thought experiment intended to reveal what they believed were inadequacies of QM. The EPR paradox hinges on the fact that under some circumstances, a pair of quantum mechanical systems can be described by a single wavefunction. When this happens, the two particles are said to be *entangled*. Consider two entangled particles , call them A and B, moving apart from each other (say along the z-axis) at nearly the speed of light. Suppose we measure an observable quantity associated with particle A, say the x-component of its spin. At the moment we make this measurement, the y-component of the spin of particle B becomes undetermined, no matter how far it is from particle A. Thus, the influence of our measurement of particle A seems to reach particle B instantaneously, which appears to violate the well-known fact that no influence can travel faster than the speed of light. Einstein called this effect "spooky action at a distance". However, since 1976, experiments have been performed which have verified that this effect is real. This has some very strange consequences, some of which have already been exploited, such as the instantaneous teleportation of photons.

Interpretations of QM [8]

There are several interpretations of QM. Although they all make the same (correct) predictions, they vary widely in their philosophical implications.

The Copenhagen Interpretation [9]
This is one of the earliest interpretations of QM and was originally the most popular interpretation among physicists. According to this interpretation, until a quantum mechanical system such as a decaying radioactive atom is observed, it is not in a well-defined state, but rather exhibits a probability distribution of being in a set of allowable states. However, once we make an observation on the system, we immediately cause it to "collapse" into one of these states. Thus, for instance, a radioactive atom is in a superposition of having decayed and not having decayed until we observe it to either having or not having decayed. As another example, an electron has a smeared-out probability distribution of its position, as described by the square of the absolute value of its wavefunction, until we observe it, when it immediately appears in a particular location. This led John Archibald Wheeler to declare, "No phenomenon is a real phenomenon until it is an observed phenomenon." [10]

Schrodinger's Cat [11]
In 1935, Schrodinger devised a thought experiment designed to present a problem with the Copenhagen interpretation. The experiment is as follows: We imagine a cat being placed in a closed box containing a radioactive substance, a Geiger counter, a hammer, and a vial of poison. Once the Geiger counter records the decay of a single atom from the radioactive substance, it triggers the hammer to strike down on the vial and release the poison, killing the cat. The problem is that if we keep the door closed, there is no way of observing the cat to determine whether it is alive or dead. According to the Copenhagen interpretation, until we open the door, the cat is neither alive nor dead but rather in a superposition of states of being both alive and dead at the same time!

The Instrumentalist Interpretation ("Shut Up and Calculate!")
This view is essentially a non-interpretation of QM, stating that the only thing that matters about QM are its predictions, which can all be derived from the mathematics of the theory. The instrumentalist view of the probabilistic nature of QM is that the probabilities merely correspond to the distribution of outcomes of repeated measurements. David Mermin summed up this position rather succinctly with his quote, "Shut up and calculate!"

The Many-Worlds Interpretation [12]
This is one of the most radical interpretations of QM, but has become perhaps the most well-accepted one in recent years. Devised by Hugh Everett in 1957, this interpretation states that every time an observation is made, the universe splits into two or more universes with different histories from that point on. Thus, the multiverse is like a tree with countless branching points, each leading to a different universe. This interpretation resolves the Schrodinger's cat paradox as follows: Once the radioactive substance decays and kills the cat, the universe branches into two distinct universes, the one in which we observe the substance to have decayed and killed the cat and another universe in which it has not yet decayed and the cat is still alive. Once we open the door, we emerge along with the cat into one of these two distinct universes.

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