A Short Introduction to Quantum Physics

Preliminary reading

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Introduction

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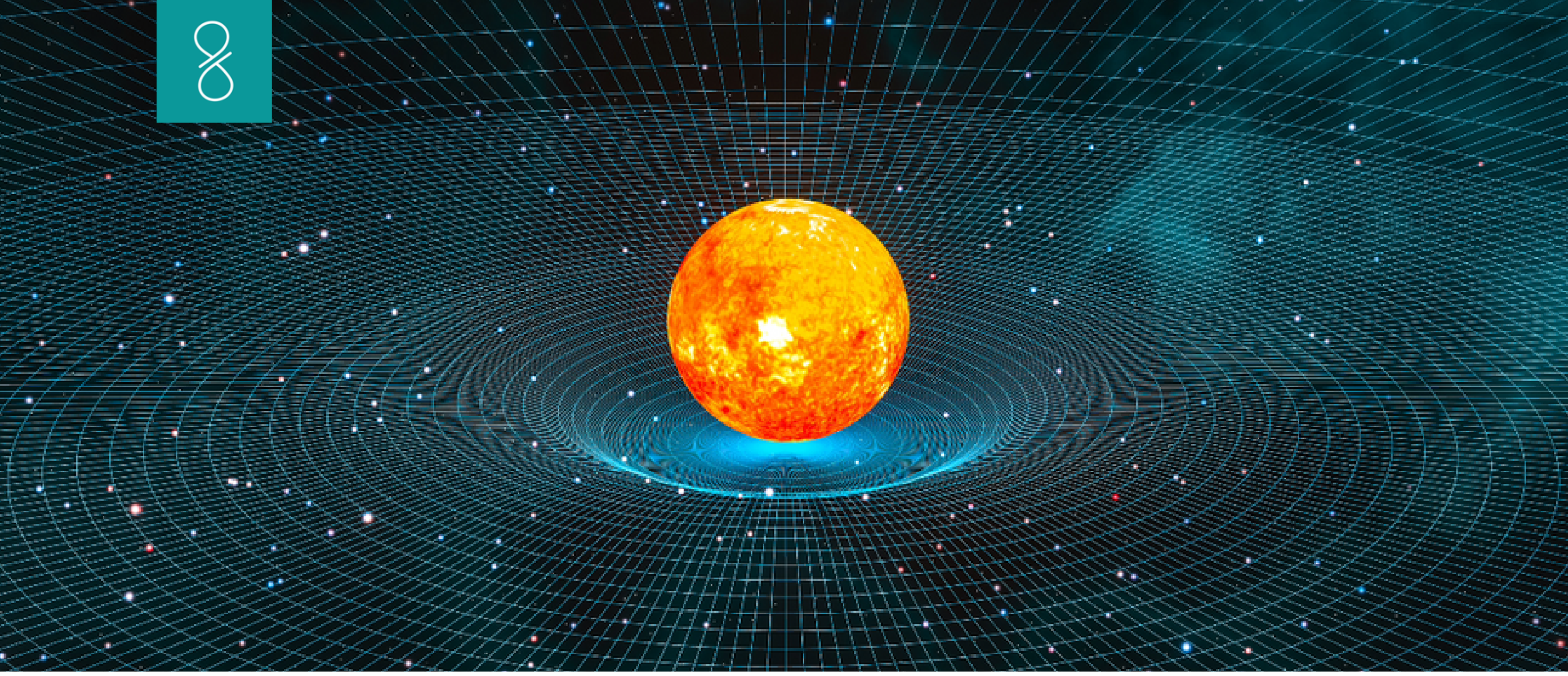
A major revolution took place in the sciences towards the end of the 19th century and the beginning of the 20th century, as many of the predictions that scientists made about the natural world turned out to be wrong or inaccurate. The mainstream theory of physics at that time was what is now known as classical physics: a theory of how objects behave in the macroscopic world we inhabit. Classical physics is a deterministic theory: it assumes that if the position and velocity of an object and all the forces acting on it are known, this is sufficient to fully predict its position and velocity at any future moment.

Classical physics works well for "everyday" speeds and sizes: it is an excellent theory for describing the motion, say, of a person riding a bicycle, or the impact between the balls used in a pool game. However, as physicists begun to realise at the beginning of the 20th century, its predictions are less reliable when the theory is applied to very small or very massive objects and to extremely high speeds. These limitations led to the formulation of two more accurate theories of physics: quantum mechanics, which deals with the microscopic world, and Einstein's relativity theory, which deals with very massive objects and/or objects moving at speeds comparable to the speed of light.

Unlike relativity theory, quantum mechanics was not discovered by a single scientist. Rather, it was developed as a collective effort by many theorical and experimental physicists throughout much of the 20th century, with the most concentrated period of pioneering activity taking place during the 1920s. In this short introduction to quantum mechanics, you will learn about the fundamental ideas of this new kind of physics, which, to date, is the most accurate theory of how matter and energy behave on a microscopic scale. Most of the concepts touched upon here will be expanded in greater detail in Module One.

The Solvay Conference on Electrons and Photons, (colourised version) **1927**.Back to front, left to right:**Back**: *Auguste Piccard, Émile Henriot, Paul Ehrenfest, Édouard Herzen, Théophile de Donder, Erwin Schrödinger, JE Verschaffelt, Wolfgang Pauli, Werner Heisenberg, Ralph Fowler, Léon Brillouin.* **Middle**: *Peter Debye, Martin Knudsen, William Lawrence Bragg, Hendrik Anthony Kramers, Paul Dirac, Arthur Compton, Louis de Broglie, Max Born, Niels Bohr.* **Front**: *Irving Langmuir, Max Planck, Marie Curie, Hendrik Lorentz, Albert Einstein, Paul Langevin, Charles-Eugène Guye, CTR Wilson, Owen Richardson.*



What is a quantum?

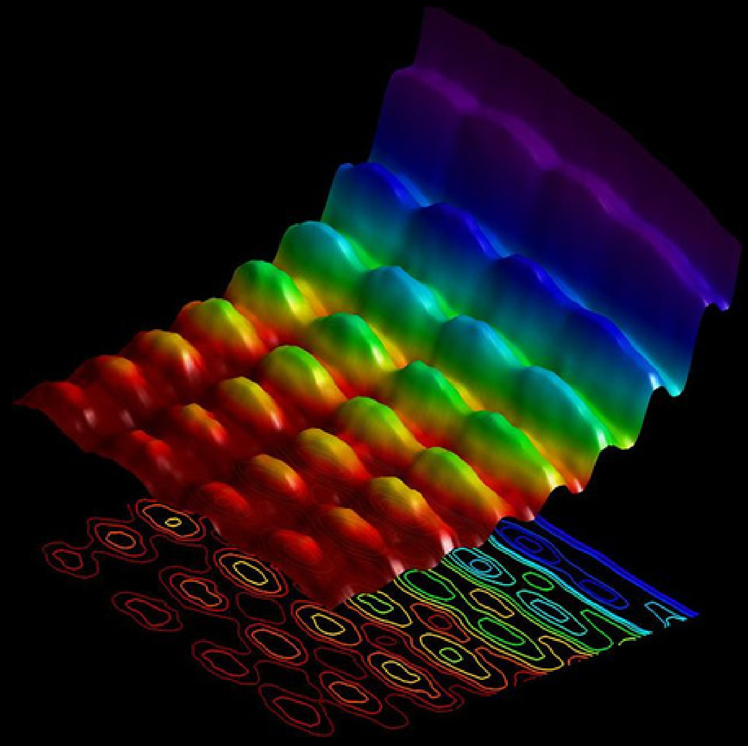
Towards the end of the 19th century, scientists had begun to realize that matter is not a continuous, uniform entity: rather, it is composed of localised units, which were called atoms (from the Greek word for “indivisible”). As it eventually turned out, atoms could in fact be divided in more elementary entities: a nucleus composed of protons and neutrons, where most of an atom’s mass is concentrated, surrounded by electrons, very light particles with a negative electric size. In turn, protons and neutrons can be subdivided into smaller elementary particles, named quarks. While many schoolbooks still depict protons, neutrons and electrons as solid spheres, nothing could be further from the truth – which is something that has been revealed by quantum physicists during the 20th century.

In 1900, Max Planck, one of the fathers of quantum physics, suggested that not only matter, but also energy was not a continuous entity, but that it was rather localised in discreet units, which he called “quanta” (hence the name quantum mechanics/physics). Later, in 1905, Albert Einstein applied this idea to light, demonstrating that it had a “particle nature”. This result was somewhat puzzling, as light also possesses a wave-like nature[1]; however, experiments clearly demonstrate that under certain conditions, it behaves as if composed of material particles instead. Each of these particles, a “quantum of light”, is known as photon, and this is the smallest amount of light of a certain energy that can be emitted: the “fundamental unit” of light. Under certain conditions, light behaves as if made up of many of these discreet photons, manifesting a particle-like behaviour. Under other conditions it reveals its wave-like nature, showing behaviours that are typical of waves, such as interference and diffraction.

Wave or Particle?

Einstein demonstrated that a wave-like phenomenon, like light, had a particle-light nature too. In 1923, another physicist, Louis de Broglie suggested that the opposite was also true: he speculated that material particles, like electrons or protons, could – under certain conditions – behave like waves. As absurd as this might seem, this prediction was in fact confirmed by experiments in the following years: this principle of wave-particle duality is now accepted as a key feature of all entities at the microscopic quantum level.

[1] In physics, the term wave is used to refer to all phenomena that display properties similar to those of a wave propagating on the surface of a liquid. Wave-like phenomena, such as light, manifest certain behaviour that are not displayed by particles, such as interference (the process of interaction between two waves) and diffraction (what happens to a wave as it spreads out through a small opening).



Probability and uncertainty

In 1925, Werner Heisenberg, together with Max Born and Pascual Jordan, provided the first mathematical description of quantum mechanics. One year later, Erwin Schrödinger formulated an independent mathematical description of quantum mechanics, based on what later became known as the "Schrödinger equation". From these two formulations, two paradoxical properties emerged:

1) Heisenberg's Uncertainty Principle states that it is impossible to know, with arbitrary accuracy, the position and the velocity of a particle at the same time. In classical physics, in principle, these two quantities can be measured simultaneously, and particles move along well-defined trajectories that can (again, in principle) be accurately calculated. But in quantum physics, the concept of trajectory breaks down: if the velocity of a particle is known with great accuracy, there will be an increasingly great uncertainty about its position, and vice versa. This principle also applies to other couples of variables, such as the energy of a physical process and the time at which it took place.

2) Schrödinger's equation describes the world as probabilistic rather than deterministic. Rather than assigning well-defined properties to a system (say, a certain position and velocity), it describes the evolution of probability waves: that is, the probability of observing certain features of a physical system. When an observation is made, this cloud of probabilities collapses into a single value (the result of a measurement), but it is impossible to know in advance which value it will be. A puzzling consequence of this theory (which has been validated through experiments) is that a physical system can be in multiple states at the same time, and it is only when a measurement is performed that one of these states manifests (you might have heard of the thought experiment known as "Schrödinger's cat", which illustrates this paradox).

Quantum Entanglement

Many physicists found it hard to abandon a deterministic description of nature in favour of a probabilistic one. Among them was Albert Einstein, who unsuccessfully tried to illustrate how quantum theory would lead to internal contradictions. In 1935, with his colleagues Podolsky and Rosen, he devised a thought experiment later known as "EPR paradox", inadvertently predicting the phenomenon of *quantum entanglement*. This phenomenon involves the instant communication between two "entangled" systems, which may be separated by enormously large distances. Measurements on the first system immediately involve a change in the quantum state of the second, and vice-versa. While Einstein and his colleagues thought this phenomenon to be impossible, and therefore prove the inconsistency of quantum theory, it has since been rigorously verified by repeated experiments – confirming the predictive power of quantum theory instead, while at the same time adding to the list of paradoxical behaviours displayed by quantum systems.

In Module 1, you will learn in more detail about such unintuitive behaviours and acquire enough knowledge of quantum mechanics to understand the material discussed throughout the rest of the course. In addition, you will encounter several different interpretations of quantum physics: the different ways scientists and philosophers tried to interpret the mathematical theory to make sense of the anomalies of the quantum world.