Age of the Atom Part 2

Max Planck (1858 – 1947)

Max Planck was a German theoretical physicist, considered to be the initial founder of quantum theory, and one of the most important physicists of the 20th Century. Physicists at the time thought that matter and energy were distinct. Matter was believed to consist of particles (e.g. protons, electrons, etc.) whereas energy in the form of light (electromagnetic radiation) was described as a wave. Around 1900, Planck realized that light and other electromagnetic waves were emitted in discrete packets of energy that he called "quanta" - "quantum" in the singular - which could only take on certain discrete values (multiples of a certain constant, which now bears the name the "Planck constant"). Thus, these quanta could be calculated according to the equation: $E = hv$ (where E is energy, h is Planck's constant, and v is frequency).

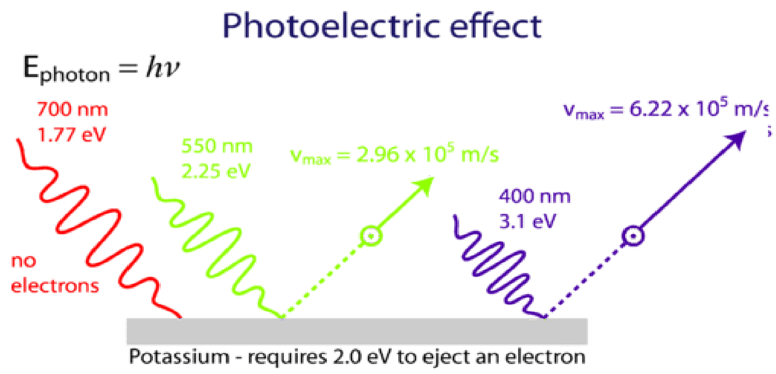
Electrons in atoms can gain or lose a quantum, meaning that electrons can gain or lose only energy values that are multiples of Planck's constant. Consider a brick wall as an analogy. A brick wall is composed of layers of bricks stacked on top of one another. The height of each layer is constant, equally the height of one brick. Think of the height of one brick as Planck's constant and the total height of the wall as the amount of energy gained or lost by an electron. The total height of the wall can be calculated by multiplying the height of one brick by the total number of brick layers. Thus, the total height is always a multiple of the height of one brick. Likewise, the amount of energy gained or lost by an electron can be calculated by multiplying Planck's constant by frequency. Thus, the amount of energy is always a multiple of Planck's constant.

Planck's theory was ground-breaking because it had always been assumed that the energy of matter was continuous, meaning that the transfer of any quantity of energy was possible. Although Planck's quantization was a purely formal assumption, its discovery has come to be regarded as effectively the birth of quantum physics, and the greatest intellectual accomplishment of Planck's career. This is generally regarded as the first essential stepping stone in the development of quantum theory, which has revolutionized the way we see and understand the sub-atomic world. Planck was awarded the Nobel Prize in Physics in 1918.

Albert Einstein (1879 – 1955)

For many years, scientists believed that light had wave properties. In 1905, Albert Einstein proposed that **light** behaves not only like a wave, but also as a particle. He called these particles of light photons. A **photon** is a particle of electromagnetic radiation that has **zero mass** and **carries a quantum of energy**, meaning a photon has a specific amount of energy. Scientists trained in classical physics found this wave-particle duality of light to be a difficult idea to accept. A key experiment that was explained by Einstein using light's particle nature was called the **photoelectric effect**.

The **photoelectric effect** is a phenomenon that occurs when light shined onto a metal surface causes the ejection of electrons from that metal. It was observed that only certain frequencies of light are able to cause the ejection of electrons.



Low frequency light (700 nm; red) is unable to cause ejection of electrons from the metal surface. At or above the threshold frequency (550 nm; green) electrons are ejected. Even higher frequency incoming light (400 nm; blue) causes ejection of the same number of electrons but with greater speed

Einstein proposed that light behaved like a stream of particles called *photons* with an energy of $E=hv$. The E is the minimum energy that is required in order for the metal's electrons to be ejected. If the incoming light's frequency, v, is below the threshold frequency, there will never be enough energy to cause electrons to be ejected. If the frequency is equal to or higher than the threshold frequency, electrons will be ejected. As the frequency increases beyond the threshold, the ejected electrons simply move faster. An increase in the intensity of incoming light that is above the threshold frequency causes the number of electrons that are ejected to increase, but they do not travel any faster.

Recap of Bohr

Bohr's model of the atom (1911) stated that electrons exist in fixed circular obits of specific energy. Bohr's model of the atom was valuable in demonstrating how electrons were capable of absorbing and releasing energy and how atomic emission spectra were created. However, the model did not really explain why electrons should exist only in fixed circular orbits rather than being able to exist in a limitless number of orbits all with different energies. In order to explain why atomic energy states are quantized, scientists needed to rethink the way in which they viewed the nature of the electron and its movement.

Louis de Broglie (1892 – 1987)

By 1905 Einstein had proposed that light, once thought to only behave like a wave, also behaves like a particle. Could the same principle apply to matter? Could matter, known to be made of particles, also behave as a wave?

In 1924, French scientist Louis de Broglie answered this question. He derived an equation that described the wave nature of any particle. Particularly, the wavelength (λ) of any moving object is given by: $\lambda=h/mv$
In this equation, h is Planck's constant, m is the mass of the particle in kg, and v is the velocity of the particle in m/s. Thus, a particle also has wave properties.

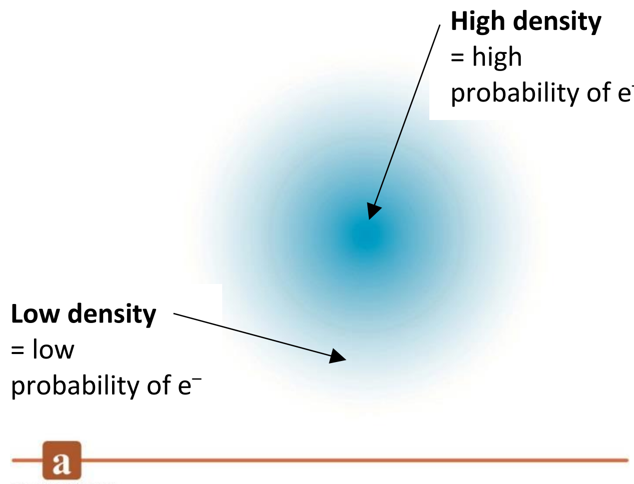
An electron, a type of particle, that is confined to a particular space around the nucleus of an atom can only move around that atom in such a way that its electron wave "fits" the size of the atom correctly. This means that the frequencies of electron waves are **quantized**. Based on the $E=hv$ equation, the quantized frequencies mean that electrons can only exist in an atom at specific energies, as Bohr had previously theorized. Today, matter waves are referred to as de Broglie waves.

Erwin Schrödinger (1887 – 1961)

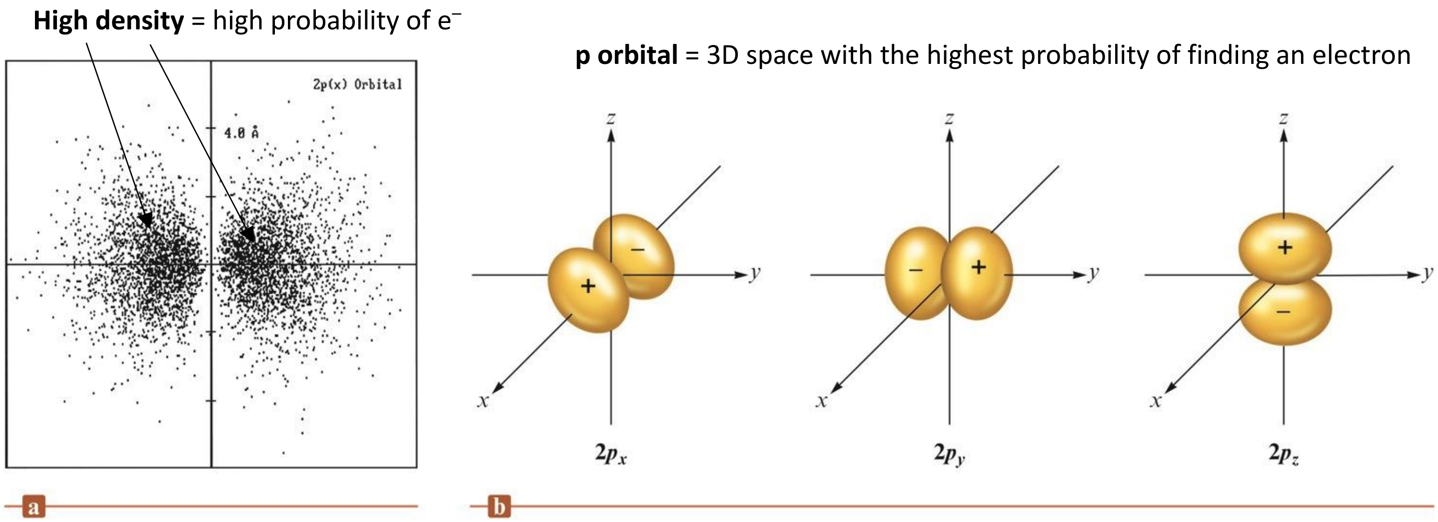
In 1926, Austrian physicist Erwin Schrödinger used the wave-particle duality of the electron to develop and solve a complex mathematical equation that accurately described the behavior of the electron in a hydrogen atom. This equation is known as **Schrödinger's wave equation**. **The quantum mechanical model** of the atom comes from the solution to Schrödinger's equation. Quantization of electron energies is a requirement in order to solve the equation. This is unlike the Bohr model, in which quantization was simply assumed with no mathematical basis.

Recall that in the Bohr model, the exact path of the electron was restricted to very well-defined circular orbits around the nucleus. The quantum mechanical model is a radical departure from that. Solutions to the Schrödinger wave equation, called **wave functions**, give only the probability of finding an electron at a given point around the nucleus. Electrons do not travel around the nucleus in simple circular orbits.

The location of the electrons in the quantum mechanical model of the atom is often referred to as an **electron cloud**. The electron cloud can be thought of in the following way: Imagine placing a square piece of paper on the floor with a dot in the circle representing the nucleus. Now take a marker and drop it onto the paper repeatedly, making small marks at each point the marker hits. If you drop the marker many, many times, the overall pattern of dots will be roughly circular. If you aim toward the center reasonably well, there will be more dots near the nucleus and progressively fewer dots as you move away from it. Each dot represents a location where the electron could be at any given moment. Because of the uncertainty principle, there is no way to know exactly where the electron is. An electron cloud has variable densities: a high density where the electron is most likely to be and a low density where the electron is least likely to be.



An electron cloud indicates a high probability of finding the electron, while the lighter region further from the nucleus indicates a lower probability of finding the electron. In order to specifically define the shape of the cloud, it is customary to refer to the region of space within which there is a 90% probability of finding the electron. This is called an **orbital**, the three-dimensional region of space that indicates where there is a high probability of finding an electron.



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Werner Heisenberg (1901 – 1976)

In 1927 another feature that is unique to quantum mechanics is the uncertainty principle. The **Heisenberg Uncertainty Principle** states that it is impossible to determine simultaneously both the position and the velocity of a particle. The detection of an electron, for example, would be made by way of its interaction with photons of light. Since photons and electrons have nearly the same energy, any attempt to locate an electron with a photon will knock the electron off course, resulting in uncertainty about where the electron is located. We do not have to worry about the uncertainty principle with large everyday objects because of their mass. If you are looking for something with a flashlight, the photons coming from the flashlight are not going to cause the thing you are looking for to move. This is not the case with atomic-sized particles, leading scientists to a new understanding about how to envision the location of the electrons within atoms.