LOUIS DE BROGLIE

Prince Louis Victor Pierre Raymond de Broglie was born in Dieppe on August 15th 1892. De Broglie first studied history, but developed an interest in physics as a result of working with his older brother Maurice. Maurice had been a naval officer where he worked on early radio systems for ship to ship and ship to shore communication. In 1904 he left the navy to study physics. Maurice pursued his interest in physics by setting up a private laboratory to study X-Rays. Maurice attended the first Solvay conference, held in Brussels in 1911, in the capacity of scientific secretary. It was after reading the proceedings of this conference, largely written by his brother, that Louis decided to abandon his studies of history and to focus instead on physics. After graduating in 1913, Louis was called up for military service. Events in Europe meant that before his military service was completed, France was at war and Louis was to remain in the army for another 4 years. His time spent in the army was not altogether wasted; he spent his military service as a radio engineer working at the base of the Eiffel tower in Paris. De Broglie resumed his studies of physics in 1920.

In 1905 Einstein had shown that the hitherto wavelike nature of light concealed an underlying particle-like nature. In 1923 de Broglie was struck with the idea that maybe this situation could be reversed, that perhaps a particle could be described in terms of wave. De Broglie discovered that if he assigned a wavelength and a frequency to an electron he could explain the location of the atoms in the Bohr model of the atom. He found that the orbiting electrons could only occupy orbits which contained a whole number of such wavelengths.

De Broglie's idea hinges around the notion of standing waves. A standing wave occurs for example in a taught string, anchored at both ends, that is plucked. The fundamental frequency occurs when the whole length of the string vibrates. Other modes of vibration are also possible, for example where the centre of the string remains stationary and the two halves of the string each vibrate at what is referred to as a second harmonic frequency. This can also happen at the third, fourth and other higher harmonics. Here then was a possible explanation as to why the electron orbits could only take on whole number multiples of a base value.

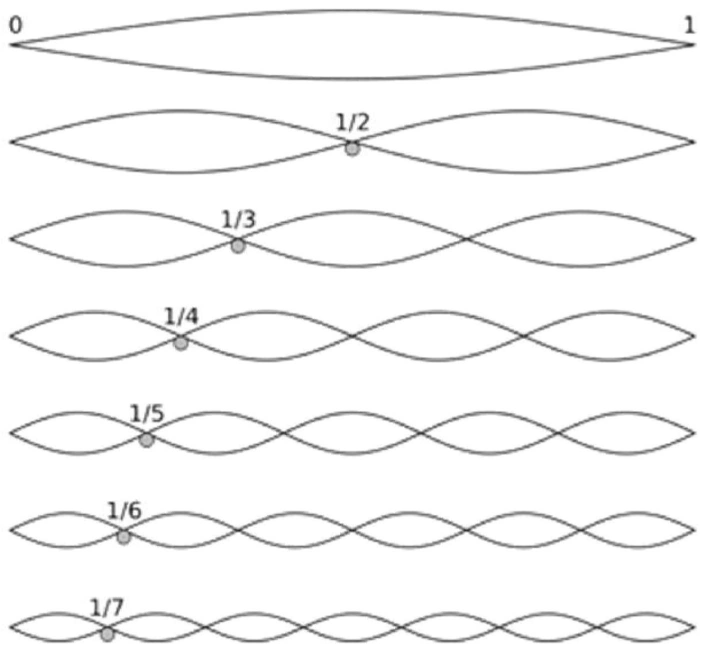

Figure 1

De Broglie supposed that the electron had a natural frequency which existed as standing wave and which described the orbit of the electron in its base energy state. The standing wave was at a frequency which equated to the orbital frequency of the electron and the wavelength was equal to the orbital path length.

At higher energy levels he found that the standing wave was at a frequency which was an integer multiple of the electron's orbital frequency and that it had a wavelength which was an integer fraction of the orbital path length. He could therefore describe the orbit in terms of a fundamental frequency in the base state and a series of harmonic frequencies in the higher energy states.

De Broglie developed a formula relating the wavelength of the electron to its mass and velocity.

$$\lambda = \frac{2\pi\hbar}{p}$$ Equation 1

Where p is the linear momentum of the particle: the product of its mass and its velocity.

Substituting the values for velocity and radius of the Bohr model in this equation:

$$v_n = \frac{Kq^2}{n\hbar}$$ Equation 2

And

$$\lambda_n = \frac{2\pi\hbar}{m v_n}$$ Equation 3

So

$$\lambda_n = \frac{2\pi n\hbar^2}{m K q^2}$$ Equation 4

But

$$r_n = \frac{n^2 \hbar^2}{m K q^2}$$ Equation 5

Which means that

$$\lambda_n = 2\pi n\, r_n$$ Equation 6

In the base state, where n = 1, the wavelength equivalent of the particle is simply 2π times the radius, that is equal to the circumference of its orbit. In the second energy state the wavelength equivalent is equal to one half the circumference of the now larger orbit and so on.

De Broglie went on to argue that it was not just the electron that had this wave equivalence but that it was true for all particles. All particles could be regarded as a wave having a wavelength based on this same formula.

$$\lambda = \frac{2\pi\hbar}{p}$$ Equation 7

The formula links the fundamental Planck's constant to the momentum of the particle. Momentum is however the product of mass and velocity, so the de Broglie wavelength is a function of both mass and velocity.

In his calculations de Broglie chose to identify the wavelength of the particle with Planck's constant, defining it as Planck's constant divided by the linear momentum of the particle.

$$\lambda = \frac{2\pi\hbar}{mv}$$ Equation 8

However this is an artificial and arbitrary device. On any other scale, from that of a star orbiting a galaxy, through a planet orbiting a star, right the way down through a conker whirled on a piece of string, down to and including the base energy state of the atom we identify the wavelength of an orbiting object with its angular momentum divided by linear momentum. De Broglie chooses not to and instead invents a new type of wave, one for which there is no real physical interpretation, based on dividing Planck's constant by the linear momentum. He does so in the full knowledge of Bohr's adopted assumption that angular momentum is an integer multiple of Planck's constant. De Broglie's standing waves are an inevitable consequence of this invention.

Objects which are in circular motion can always be associated with a wave. The wave simply describes the motion of the object in one axis, normally the axis which along which the observer views the orbiting object. The diameter of the orbit is then the amplitude of the wave, the circumference is the wavelength and the tangential velocity of the orbiting object is identified with the velocity of propagation of the wave.

The radius of the orbit of such an orbiting object can then simply be calculated by dividing the angular momentum of the object by its linear momentum; a fact which derives directly from the definitions of these two quantities. This holds true for any object in orbit, so for example the orbital radii of the moons of Jupiter can be calculated by dividing their angular momentum by their linear momentum.

$$R = \frac{mvr}{mv}$$ Equation 9

The wavelength of such wave is then simply the radius multiplied by 2π

$$\lambda = 2\pi \frac{mvr}{mv} = 2\pi R$$ Equation 10

In Bohr's model the angular momentum is an integer multiple of Planck's constant.

$$l = n\hbar$$ Equation 11

$$R_n = \frac{n\hbar}{mv}$$ Equation 12

So the wavelength of the particle is no longer the radius of the generating circle multiplied by 2π, it is the radius times 2π divided by n.

$$\lambda_n = 2\pi \frac{R}{n} \qquad \text{Equation 13}$$

De Broglie's harmonics are therefore a direct result of him applying Bohr's adopted assumption that the angular momentum of the orbiting electron can only take on values which are integer multiples of Plank's constant while at the same time identifying the wavelength of the particle, not with its angular momentum, but with Planck's constant. Viewed in this light de Broglie's contribution amounts to nothing more than a restatement of the Bohr model using different language; the language of waves and frequency rather than that of particles. In effect de Broglie's harmonics are as artificial as Bohr's and Nicholson's assumption and can be seen as a contrivance rather than an insight into the mechanics of the atom.

De Broglie published his results as his PhD Thesis in 1924 and was subsequently awarded the Nobel Prize for physics in 1929.

De Broglie was less than satisfied with his own ideas on the wave nature of matter and in particular was concerned to establish the link between his new wave mechanics and classical mechanics. His early attempts were abandoned in 1927 due to the adherence of physicists to the probabilistic interpretation of Born, Bohr, and Heisenberg. He resumed this search in 1951 and spent much of the rest of his life trying to find such a link. What de Broglie was looking for was a causal relationship between the mechanics of his waves and classical mechanics. In effect this is the same as looking for a mechanism in the classical domain which leads to quantisation of angular momentum. Needless to say de Broglie was not successful in this search. He does however provide us with a number of useful insights.

Firstly de Broglie recognises that the discrete energy levels of the atom are in some way associated with a harmonic sequence. That is with a series of frequencies which are an integer multiple of a base or fundamental frequency. A harmonic sequence appears in the frequency domain as a series of impulses equally spaced equally along the frequency axis F Hz apart and forming what is commonly referred to as a Dirac comb. The inverse Fourier transform of such a Dirac comb into the time domain is itself a Dirac comb, or series of impulses equally spaced along the time axis T seconds apart where T=1/F. Such a series of impulses in the time domain corresponds to a sampling process. The uniqueness of the Fourier transform means that if ever we encounter a harmonic series in the frequency domain there must be a corresponding sampling process taking place in the time domain. In this case the sampling frequency is equal to the orbital period of the orbiting electron. That is there must be something that happens within the atom which occurs or can occur only once per orbit of the electron.

De Broglie's second insight comes in recognising that there is some sort of frequency multiplication process taking place within the atom. In the case of de Broglie, this is confined to the domain of the orbiting electron in the form of his harmonic waves where in the n^{th} energy state he cites a frequency of n times that of the orbiting electron. The problem with this is that there is no physical way to interpret such waves, the fastest moving object in the atom is the orbiting electron itself and it does so at the fundamental frequency. Nothing about the electron is oscillating at any higher frequency than this, at least nothing that can be said to be real. There is however one circumstance where such frequency multiplication does occur naturally; and that is under conditions of relativity.

Some of the most compelling evidence for the effects of relativity comes in an experiment carried out at CERN in 1977 called the Muon Ring Experiment. Muons are charged particles much like an electron, only more massive. When observed at low, non-relativistic, speeds they have an average lifetime of 2.2µsecs after which time they decay into an electron and two neutrinos. In the experiment muons are injected into the 14m diameter ring at 99.94% of the speed of light where Gamma has a value of almost 30. The muons now appear to have lifetime of some 65µsecs or Gamma times that which they have at non-relativistic speeds. This is because the processes which take place inside the muon and eventually lead to its decay are doing so in an environment where time is running slower by a factor of 30. Hence as far as the muon is concerned, it still has a lifetime of 2.2µsecs, but as far as us stationary observers are concerned it has a lifetime of 65µsecs. Travelling for 2.2 microseconds at close to the speed of light you would expect the muon to cover some 660m or roughly 14 times around the ring, but in fact it is observed to travel some 20,000m or 440 times around the track. This comes about because for the muon, travelling at near light speed, distance is foreshortened by a factor Gamma. So as far as the muon is concerned, it has travelled 660m, but to us stationary observers, where distance is not foreshortened, this appears as 20,000m.

Both parties agree that the muon passes a fixed reference point on the ring some 440 times during its lifetime. For us stationary observers that is 440 times in 65µsecs or roughly 6.8mHz. For the muon however the 440 turns around the ring are completed in just 2.2µsecs, corresponding to a frequency of 200mHz. For the muon, indeed for any object in orbit under relativistic conditions, orbital frequency is increased by a factor Gamma. We see the muon as travelling some 20,000m during 440 cycles around the ring or .022 revolutions/m. The muon, on the other hand sees itself as travelling some 660m in 440 turns or .667 revolutions/m. Hence for objects travelling at near light speed both temporal and spatial frequencies are multiplied by Gamma. This really is quite a remarkable result, there is no other phenomenon where both temporal and spatial frequency is multiplied in this way.

De Broglie failed to find a way to justify the wave mechanics for which he is now credited. In doing so however he provides use with useful insights into the inner workings of the atom. The discrete energy levels of the atom are associated with a harmonic sequence. This is inevitably associated with some sort of sampling process taking place within the atom. There is also some sort of frequency multiplication taking place and this is most likely associated with the effects of relativity. The electron orbiting the hydrogen nucleus must therefore be doing so at near light speed, where these effects become significant and not at the much lower Bohr velocity that current models suggest.

These ideas are explored more fully in Sampling the Hydrogen Atom.