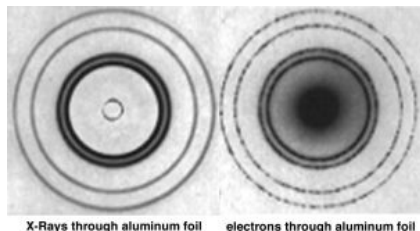


2.4: Beyond Bohr

Eventually, as they considered the problems with the Bohr model, scientists came back to the idea of the wave-particle duality as exemplified by the photon. If light (electromagnetic radiation), which was classically considered to be a wave, could have the properties of a particle, then perhaps matter, classically considered as composed of particles, could have the properties of waves, at least under conditions such as those that exist within an atom. Louis De Broglie (1892–1987) considered this totally counterintuitive idea in his Ph.D. thesis. De Broglie used Planck's relationship between energy and frequency ($E = hn$), the relationship between frequency and wavelength ($c = \lambda n$), and Einstein's relationship between energy and mass ($E = mc^2$) to derive a relationship between the mass and wavelength for any particle (including photons).^[12] You can do this yourself by substituting into these equations, to come up with $\lambda = \frac{h}{mv}$, where mv is the momentum of a particle with mass m and velocity v . In the case of photons, $v = c$, the velocity of light.



Although the math involved in deriving the relationship between momentum (mv) of a particle and its wavelength λ is simple, the ideas behind it are most certainly not. It is even more difficult to conceptualize the idea that matter, such as ourselves, can behave like waves, and yet this is consistent with a broad range of observations. We never notice the wavelike properties of matter because on the macroscopic scale, the wavelength associated with a particular object is so small that it is negligible. For example, the wavelength of a baseball moving at 100 m/s is much smaller than the baseball itself. It is worth thinking about what you would need to know to calculate it. At the atomic scale, however, the wavelengths associated with particles are similar to their size, meaning that the wave nature of particles such as electrons cannot be ignored; their behavior cannot be described accurately by models and equations that treat them as simple particles. The fact that a beam of electrons can undergo diffraction, a wave-like behavior provides evidence of this idea.

Certainty and Uncertainty

Where is a wave located? The answer is not completely obvious. You might think it would be easier to determine where a particle is, but things get complicated as they get smaller and smaller. Imagine that we wanted to view an electron within an atom using some type of microscope, in this case, an imaginary one with unlimited resolution. To see something, photons have to bounce or reflect off it and then enter our eye, be absorbed by a molecule in a retinal cell, and start a signal to our brain where that signal is processed and interpreted. When we look at macroscopic objects, their interactions with light have little effect on them. For example, objects in a dark room do not begin to move just because you turn the lights on! Obviously the same cannot be said for atomic-scale objects; we already know that a photon of light can knock an electron completely out of an atom (the photoelectric effect). Now we come to another factor: the shorter the wavelength of light we use, the more accurately we can locate an object.^[13] Remember, however, that wavelength and energy are related: the shorter the wavelength the greater its energy. To look at something as small as an atom or an electron we have to use electromagnetic radiation of a wavelength similar to the size of the electron. We already know that an atom is about 10^{-10} m in diameter, so electrons are presumably much smaller. Let us say that we use gamma rays, a form of electromagnetic radiation, whose wavelength is $\sim 10^{-12}$ m. But radiation of such short wavelength carries lots of energy, so these are high-energy photons. When such a high-energy photon interacts with an electron, it dramatically perturbs the electron's position and motion. That is, if we try to measure where an electron is, we perturb it by the very act of measurement. The act of measurement introduces uncertainty and this uncertainty increases the closer we get to the atomic molecular scale.

This idea was first put forward explicitly by Werner Heisenberg (1901-1976) and is known as the Heisenberg Uncertainty Principle. According to the uncertainty principle, we can estimate the uncertainty in a measurement using the formula $\Delta mv \times \Delta x > \frac{h}{2\pi}$, where Δmv is the uncertainty in the momentum of the particle (mass times velocity or where it is going and how fast), Δx is the uncertainty in its position in space (where it is at a particular moment), and h is Planck's constant now divided by 2π . If we know exactly where the particle is ($\Delta x = 0$) then we have absolutely no information about its velocity, which means we do not know how fast or in what direction it is going. Alternatively, if we know its momentum exactly ($\Delta mv = 0$), that is, we

know exactly how fast and in which direction it is going, we have no idea whatsoever where it is! The end result is that we cannot know exactly where an electron is without losing information on its momentum, and vice versa. This has lots of strange implications. For example, if we know the electron is within the nucleus ($\Delta x \sim 1.5 \times 10^{-14} \text{ m}$), then we have very little idea of its momentum (how fast and where it is going). These inherent uncertainties in the properties of atomic-level systems are one of their key features. For example, we can estimate some properties very accurately but we cannot know everything about an atomic/molecular-level system at one point in time. This is a very different perspective from the one it replaced, which was famously summed up by Pierre-Simon Laplace (1749–1827), who stated that if the positions and velocities of every object in the universe were known, the future would be set:

We may regard the present state of the universe as the effect of its past and the cause of its future. An intellect which at a certain moment would know all forces that set nature in motion, and all positions of all items of which nature is composed, if this intellect were also vast enough to submit these data to analysis, it would embrace in a single formula the movements of the greatest bodies of the universe and those of the tiniest atom; for such an intellect nothing would be uncertain and the future just like the past would be present before its eyes. — Pierre-Simon Laplace (1745-1827)

It turns out that a major flaw in Bohr's model of the atom was that he attempted to define both the position of an electron (a defined orbit) and its energy, or at least the energy difference between orbits, at the same time. Although such a goal seems quite reasonable and would be possible at the macroscopic level, it simply is not possible at the atomic level. The wave nature of the electron makes it impossible to predict exactly where that electron is if we also know its energy level. In fact, we do know the energies of electrons very accurately because of the evidence from spectroscopy. We will consider this point again later in this chapter.

? Questions

Questions to Answer

- How does the wavelength of a particle change as the mass increases?
- Planck's constant is $h = 6.626 \times 10^{-34} \text{ J} \cdot \text{s}$. What are the implications for particles of macroscopic size? (1 J = the kinetic energy of a two-kilogram mass moving at the speed of 1 m/s.)
- What would be the wavelength of the world-record holder for the 100 – m sprint? What assumptions do you have to make to answer this question?
- What is the wavelength of a protein of 60,000 daltons? (That is, if the protein has a molar mass of 60,000 g/M, what is the mass of one molecule of the protein?)

Questions to Ponder

- What is the uncertainty in your momentum, if the error in your position is 0.01 m (remembering that Planck's constant $h = 6.626068 \times 10^{-34} \text{ J} \cdot \text{s}$)?
- How is it that we experience objects as having very definite velocities and positions?
- Does it take energy to determine your position?
- How is the emission and absorption behavior of atoms related to electron energies?

This page titled 2.4: Beyond Bohr is shared under a CC BY-NC-SA 4.0 license and was authored, remixed, and/or curated by Melanie M. Cooper & Michael W. Klymkowsky via source content that was edited to the style and standards of the LibreTexts platform.