8.5 Two ideas leading to a new quantum mechanics
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Key Equations:

$$\lambda = \frac{h}{mu}$$ (Debroglie Wave equation)

$$\Delta x \bullet \Delta p \geq \frac{h}{4\pi}$$ (Heisenberg Uncertainty Principle)

This section is a turning point in the study of quantum mechanics. Before these two ideas, the atom was assumed to be like a planetary system with the nucleus at the center and electrons circling around it. Although Bohr's atom had incorporated Planck's hypothesis, it was still not perfect.

First of all, Bohr mixed classical physics with Planck's hypothesis. He assumed that electrons would circle the nucleus in perfect circular orbits, which has no experimental basis. His assumption of quantized angular momentum was forced into classical physics. More importantly, Bohr's model of the atom could not predict the energies and line spectra of multielectron atoms. Bohr's model explained some experimental results for single electron atoms and that's really it.

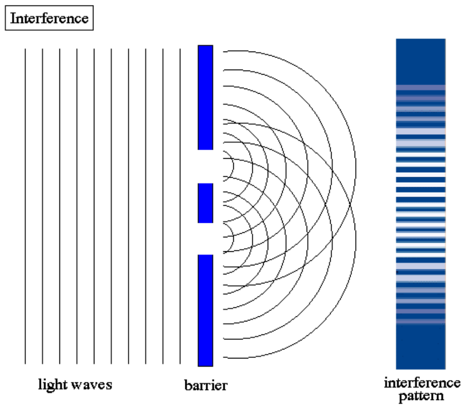
Lets go back to 8.3 for a second. We discussed the results of the photoelectric effect there and talked how Einstein was able propose the idea that light behaves like particles, which we call photons.

The story doesn't end there though. You see, light also exhibit wave characteristics. (That's why light was assumed to behave like a wave in the earlier days - it showed all the characteristics of a wave!) Since we are not studying physics, I won't go into the details of these characteristics. I will briefly go over them here.

#1 Refraction:

Bending of light at different mediums (medium is the material that light travels in)

#2 Interference :



Light waves interfere with each other much like the way water waves do. Complex interference patterns are sometimes referred to as diffraction. (You should have heard of diffraction, maybe in terms of x-ray diffraction in your previous Biology classes. Rosalind Franklin conducted x-ray diffraction that lead to the discovery of DNA structure by Watson and Crick.)

So, what do we do? We can't say light is a particle because it has wave characteristics. We can't say that light is a wave either because sometimes it acts like particle. We are at a deadend here. Thankfully, some genius, I don't know who, suggested that maybe light is both a particle and wave! This is called the wave-particle duality for light. This is not to say that light is both a wave and a particle at the same time. No! It means that light acts like a particle in certain situations and acts like waves during other times. You following?

Then Mr.De broglie came along. You see, De Broglie is a smart fellow that likes to question things he learned. He asks himself, if light can exhibit both wave and particle behaviours, is this also true for matters? We know that matters are made of particles (think atoms), so he is saying.. can particles also exhibit wave behaviours? Well, no one answered him because no one really knows. This is the perfect opportunity for De Broglie to shine. He proposed that all particles should be regarded as having wavelike properties. He even made a nice little equation that would calculate the wavelength of any particle. (When we think of particles, we think of small balls. In this context, particles mean any physical object) Here is how he got his equation.

He took two energy equations, one from Einstein and one from Planck. He "mated" them.

$E = mc^2$ (The most famous equation in physics, from Einstein)
$E = h\nu$ (Planck's equation)

Since they both equal to energy, he made them equal to each other.
$mc^2 = h\nu$

but we know $\nu = \frac{c}{\lambda}$

$mc^2 = h\ \frac{c}{\lambda}$

$mc = \frac{h}{\lambda}$

$\lambda mc = h$

$\lambda = \frac{h}{mc}$

Here is where it becomes a bit weird.. He replaced c with u. The symbol c stands for the speed of light. We know photons (which travels at the speed of light) exhibit wavelike behaviours. Is this also true for objects traveling at ordinary speed u (hence ordinary particles?)

Here is where De Broglie made a big assumption. He assumed that yes, it is true, ordinary particles do exhibit wavelike behaviours. Thus, we have:

$\lambda = \frac{h}{mu}$

Now, this idea was very radical at the time and it had no experimental backup. It was rejected pretty much by everyone until Einstein came along supported it. Einstein's support brought a number of experimenters to test this theory. The experimenters you have to know for this midterm are Davisson and Germer. Those two did an experiment together in where they observed diffraction patterns for electrons. Now, this experiment is very because it proved that electrons have both wavelike and particlelike properties; thus, their wavelike properties must be taken account when describing the structure of atoms. This is key concept that will come into play very soon.

Erm, when I said very soon, I mean now. We are going to talk about Heisenberg's uncertainty principle. Heisenberg's uncertainty principle doesn't seem to connect to De Broglie 's particle-wave theory at all. No connection was made in our textbook and the professor didn't not establish any connections either. Well, there is actually a very big connection.

In classical mechanics, a particle has a definite trajectory, or path on which location and linear momentum (momentum is mass x speed, linear momentum means momentum on a straight line) are specified at each instant. We cannot determine the precise location of a particle if it behaves like a wave. A good analogy of this is the wave on a guitar string. It is spread apart, not localized on a specific point. You cannot simply point to a place and say this is the location of the wave.

As a result, although you can determine the precise linear momentum of a particle, you cannot pinpoint its precise location. Thus, you cannot specify the trajectory of the particle. (Since trajectory depends on knowing both the precise location and the precise momentum) If you can't specify the trajectory of particle, you don't know where the particle is going to go. Thus, if we know that a particle is here at one instant, we can say nothing about where it will be an instant later.

What I just described is a crucial part of Heisenberg's uncertainty principle. Heisenberg's uncertainty is a bit more complex. The basic definition is that you cannot determine precisely the position and momentum of a particle at the SAME TIME. Keyword here is SAME TIME. Yes, you can determine one of them precisely but by doing so, you have changed conditions so that it is impossible to determine with precision the value of the other variable. Thus, when we get into atoms and such, there is always an uncertainty associated with trying to describe electrons.

Expressed quantitatively, it states that if the location of a particle is known to within an uncertainty Δx, then the linear momentum parallel to the x-axis can be known only within an uncertainty Δp.

$$\Delta x \bullet \Delta p \geq \frac{h}{4\pi}$$

This equation tells us that if the uncertainty in position Δx is very small, then the uncertainty in momentum must be very large, and vice-versa. ≥ means "greater than or equal", so the minimum value of the product of uncertainties is $\frac{h}{4\pi}$.

NOTE: Heisenberg's uncertainty principle only has an effect when we describe sub-atomic particles like electrons. It has no applications in the real macroscopic world. In the real world, I am darn certain where I am going and where I will end up.

That wraps up 8.5.