Modern Atomic Theory

Electromagnetic Radiation and the Idea of Quantum

The Heisenberg Uncertainty Principle Page [1 of 2]

We've learned that the Bohr model took an existing model of electrons orbiting around a nucleus, the same model used to describe motions of planetary bodies, but added to it that the orbits were specified values, and therefore the energies of the electrons were specified values. In other words, the energy of the electrons was quantized. Well, if indeed these electrons did still behave by the classical laws of physics, then if we could simply locate the position of an electron in a hydrogen atom, and if we knew its energy, we would then be able to know where that electron was precisely at any instant in time from that point forward. So wouldn't it be wonderful if we could simply find that electron? Well, it turns out that we can't do that. It turns out that we're never going to be able to answer that question of where exactly is the electron and what direction is it moving, and specifically what exactly is that momentum, and the reason for that is the theme of this tutorial.

In order to better understand the problem that we're facing, let's think about how we perceive where macroscopic objects are. In other words, if I am trying to figure out where this coffee cup is, I rely on particles of light to bounce off this coffee cup and enter my eye and I can see where this is based on bombarding this coffee cup with projectiles. Although these projectiles are very small compared to the coffee cup – I'm talking about the now the photons of light – I can perceive this coffee cup. Now, I have a limitation in that the wavelength of the light that I'm using must be smaller than the object I'm trying to view if I'm going to be able to get an accurate view of exactly where it is.

So, for instance, let's suppose that you're out at sea on a battleship some place and you're looking for the enemy some other place in the ocean. And here is the enemy. And you're using microwaves in a radar set-up and you can see on your radar screen a little blip corresponding to this ship. And maybe your radar's really good so you can tell that it's a big ship, maybe it's a carrier instead of a destroyer or a PT boat or something. But what you can't tell is how many people are on board or whether they have a ring on their finger. You can't get the kind of detail that you could get if you were using visible light, like we use in cameras. If you're using a telescope for instance, you're relying on visible light rather than microwaves. Visible light, if we go back to our electromagnetic spectrum, has a much smaller wavelength and therefore we get much higher resolution. The only problem is that by going to higher resolution and again, smaller wavelength, we know that that requires us to go to higher frequency and by the Planck relationship, higher frequency implies a higher packet of energy delivered with each photon. That could be a problem.

Suppose that we're trying to get more detail still. Suppose we're not satisfied with just knowing how many people are on deck, but we want to know what their pores look like. We want to be able to explore them in infinite detail. So we might go from visible light to ultra-violet light to get an even more clear glimpse of just what we're looking at in our object here.

Once again, as we go to ultraviolet light, we go to smaller wavelength. It gives us higher resolution, but we have more energy in each photon that we're using to probe and so now we can see pore size, but we're also noticing as we're watching that their skin is darkening somewhat as these photons are causing damage in their skin because they're ultra-violet. We could go to x-rays and try to get into the molecular structure, but of course, we're causing a tremendous amount of damage. We'll probably killed most of these people simply by trying to observe them. We're changing the thing we're trying to observe by trying to prove where they are.

So, in other words, let's return now to the issue of the atom. If our goal, again we said earlier, if our goal is try to locate this electron then, we need to be able to use the smallest particle possible. For us that's going to be a photon, but what photon should we choose? We could use very easily visible light, infrared light, that's a low energy photon. It's not going to have a significant impact on where the electrons are, we hope. But it's low enough energy that the wavelength is big enough that we're not going to be able to tell with any detail exactly where the electron is. In order to have a wavelength sufficiently small that we can find the electron accurately, we need to go much higher frequencies. Higher frequency means higher energy.

Suppose I wanted to locate the position of our cat that we have in the studio, Schrödinger. So I'm going to try to find that cat using particles that are about the same size, have about the same momentum if you will, as the object I'm probing. So I'm going to blindfold myself because I don't have any photons now. I can't use photons. But I have these particles and so I'm going to try to locate not on the position of Schrödinger, of our cat, but also the direction that Schrödinger is walking.

So here I go. First of all, I've got to locate Schrödinger, right here. I found Schrödinger. Now, I'm going to find out where he is next and I'll be able to figure out what direction he's walking. Now, of course the problem with this experiment is that after I hit the cat the first time, the cat’s probably headed across the street. So I have changed the direction of the thing I’m probing, and so I don’t know the momentum, because in trying to measure the position of where the cat was initially, I changed it’s momentum. That’s the same problem we run into when we try to measure where an electron is and what direction it’s going. If we try to probe for it with sufficient amount of energy that we can get good resolution on where it is, we perturb the system and we change where it’s going. So we’re stuck with this problem. We can never answer the question exactly where is the electron and where is it going.

Heisenburg says this mathematically in the Heisenburg Uncertainty Principle. Mathematically it looks like this. The error in the momentum, and remember this has directionality associated with it as well, the error in the momentum multiplied by the error in knowing the position must always be equal or greater than Planck’s constant over 4π .

This is a very, very small number so that when we’re dealing with macroscopic objects, it’s not a problem. We can locate the position of baseballs and cats using photons with a pretty high degree of accuracy. But we can never know precisely where it is and as we get to very, very small objects, we have more and more problem with this in knowing the position and momentum exactly in the object.

So, once again, the Bohr model, although it was very successful in that it gave us this notion of electrons in quantized energy levels and being at quantized distances from the nucleus. In fact, the Heisenburg Uncertainty Principle causes this model to no longer be useful for us and we’re going to abandon the Bohr model because we know that we cannot locate the electron’s momentum and position precisely. So although we can say there’s Saturn. I know its energy. I know its distance. I’ll know where Saturn is from every point thereafter; we can’t do that with an electron.