Modern Atomic Theory

Electromagnetic Radiation and the Idea of Quantum

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In 1887 Hertz made an observation that again turned out to be crucial point in the development of quantum mechanics. Let me describe this experiment for you. This is referred to as the photoelectric effect. What he observed was that if you took a block of metal, let's say potassium, and radiated it with light, that you could, in fact, kick out electrons from that metal—eject electrons from that metal. You could collect the electrons. In fact, you actually could fairly easily, with the instruments of the day, determine what the kinetic energies were of these electrons that were being emitted from this metal.

Now, here's the really amazing part. As you adjust the properties of this light, you can adjust how these electrons are being kicked out. But here's the interesting thing. If you increase the intensity of the light, you might think that the electrons that are coming off will come off with a greater kinetic energy, and in fact, that turns out not to be true, that adjusting intensity you get more electrons kicked off, but they don't come of with any higher kinetic energy. But if you change the frequency of the light you're radiating, that does correlate very strongly with the kinetic energy of the electrons coming off. Now, that's peculiar. Our intuitive feeling here is that the more intense the light is the more energy there must be in that light, and so the more energy you must have in these electrons that you're kicking out, but not so. The frequency of the light ends up being much more the important player here in this kind of an experiment. How could that be?

Let's look at the data, again, what that would look like, because something else shows up very interesting. Out here—this is a plot of the frequency of the light and the kinetic energy of the electrons that are being ejected. You'll notice here again this blue curve. What you see is as we lower the frequency of light, no matter what the intensity is, we lower the kinetic energy of the electrons that are being ejected. Okay, good enough. But if we drop the frequency too far, we reach what's called a "threshold frequency," and below that threshold, no matter how intense the light is, we don't get a single electron emitted. Very strange. Something is very special about that frequency, below which, again, we get no activity at all—no electrons are being kicked out. So how do we explain this?

Well, it took Einstein several years later to come up with a satisfactory explanation of what's going on in the photoelectric effect. Here's the idea—going back to this experiment for a moment. The thought is that light, just like energy, could be delivered in packets rather than any arbitrary amount. Instead of thinking of light as a wave that could have any arbitrary amplitude, what if light was delivered in discreet packets of energy called a "photon"? One packet of energy would be a photon, and borrowing from Planck, the idea would be that if light were quantized, the energy of that light, of that photon of light, would be proportional to the frequency of the light times—in this case—Planck's constant. This says higher frequency of light, the more energy is delivered in one packet of that light. The explanation of the photoelectric effect comes in saying, "Okay, if we're talking about individual packets of light, and we except the idea that it only takes one photon, one packet of light to eject an electron, well, you have to have sufficient energy in that photon of light to pry the electron away from what's holding it in the middle, which is a tract of forces between the electron and the nuclei. There's an electrostatic attraction of those electrons and the nuclei in the metal keeping those electrons there, and we have to overcome that energy in order to pull the electron out, and we need that energy to arrive in one packet of energy—one photon of energy in order to do that. If we don't have enough energy in a packet of light, in one photon, we can't get the electron out. What if we have too much? If we have too much energy in the photon of light, the electrons will come out and it will have a little of that energy left over. It hasn't used all of the energy in getting out of the potential well, if you will, of the metal.

We talk about that energy as a work function. We call that the work function of the metal, that is, the energy required to pay, if you will, in order to get the electron out. Coming back to our graph for a moment, where does the work function show up here? The work function would be that amount of energy that must be added before we start to get any electrons actually coming out.

Now, if this is sounding a little fuzzy to you still, let me give you an analogy. My two children love soccer. Let's imagine that we take a pit—so the soccer field is down here some place—and we put my son at the bottom of the pit with his soccer ball, and we ask him to kick the ball as hard as he can. He will be delivering in our analogy one quantum of energy to the soccer ball, a given amount of energy. That soccer ball, let's say, doesn't make it out of the pit. It only gets up this far and then it just rolls right back down to him. No matter how many times he kicks that ball the ball will roll up and come back down. We say in the terms of the photoelectric effect that one quantum of energy, at least for him, is not sufficient to get the ball out of the potential well, to get the soccer ball out of this pit. It costs us this amount of energy to do that, and he doesn't have enough. This is the work function, if you will.

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Now, let's replace him with his sister. She's a couple of years older. He's not going to like this if he finds out I said this. She can kick the ball harder. So let's say that she kicks the ball with a bigger quantum of energy, and it's enough energy to get the soccer ball out of the pit. In fact, not only is it enough, but there's a little bit left over, so the ball starts to roll away. That's kinetic energy in the soccer ball left over from what she put into it down here. But we've lost this much of the energy just getting the ball out of the pit.

Now you put me in the pit. I'll miss the soccer ball, but let's say for the sake of argument that I could kick the thing. I'd be able to get it out of the pit and I would be delivering more energy so there would be more energy left over, so the soccer ball rolls away from the pit with a greater amount of kinetic energy—again, more energy left over.

Going back to the photoelectric effect and the analogy here, the electron is in a potential well—again, this is the work function of the metal. We put in a certain amount of energy—that's the kick. It costs us a certain amount of energy to get the electron out, but whatever is left over shows up as kinetic energy of the electron. So that does a nice job then of explaining the data. Again, here there's not enough energy to get out of the pit if we're at low frequencies. Remember, low frequency of light means lower amounts of energy in the photon, but eventually we reach the threshold frequency, which means that the energy of the photo is sufficient to just equal the work function—how deep the well is—and anything after that is gravy. Any extra energy we have because of higher frequency means more energy. Any extra energy we have shows up as just kinetic energy. Kinetic energy, again, of the electron.

Let's see what this might look like if we had a problem. Let's suppose that we have the following problem: The longest wavelength of light capable of ejecting an electron from the surface of zirconium is 306 nanometers. What's the work function for zirconium. What are we doing? We're changing the metal, let's say, from potassium to zirconium, something that because the nuclear charges are different, the number of electrons are different, has a different ability to hold the electrons. In other words, the work function will change as we change the metal, because again, these nuclei have differing amounts of ability to hold on to the electrons. So we're going to determine what the work function is of zirconium given the observation that the lowest energy photon has a wavelength of 306 nanometers. That will be the threshold frequency that we could derive from this number.

So how do we do that? Well, we know that the threshold frequency is related to the threshold wavelength, if you will. Remember, that is the longest wavelength allowed. Anything longer than that works. If I plug that in I find out what the smallest frequency is that's allowed, and again, that's the threshold frequency. If I plug that in I end up with a threshold frequency of 9.8 x 10^{14} per second—hertz, in other words.

Now, we're not done yet, because we know that the energy of the photon, if we are at a frequency that is just the threshold frequency, that that energy will be, in fact, the work function. Remember? This is now talking about putting in a photon that's just enough energy to get the electron out of the well and no more. That would be the work function of the metal. So once again, plugging in Planck's constant, and the frequency, the threshold frequency, we arrive at the energy of the photon that's needed, or in other words, the work function of the metal. We end up, in this case, with 6.5 x $10^{19\text{ joules}}$, or if we want we can convert that into another unit of energy—electron volts. So this is a typical type of a problem you'd see having to do with the photoelectric effect.

But the photoelectric effect is much more important than solving problems. The photoelectric effect forever changes the way we think about light. It says that light is quantized, that you can't have any arbitrary amount of light, that you must have certain amounts of light that arrive in packets of energy called a "photon." Each packet is called a photon. The interesting thing about all of this is that if it's true that one photon of light is sufficient to move an electron out of a piece of metal, it also might be true, and in fact, it is true, that one photon of light is sufficient to move an electron from one place in a molecule to another place, and that that may result in a chemical reaction that ultimately may lead to a signal that reaches your brain, that tells you the photon got there. In fact, your eye is one of the most sensitive detectors we know of. Your eye can detect a single photon of light that triggers a molecular event that ultimately tells you, "Hey, you saw some light." Whether that photon is coming from a candle three feet away or a star a billion light years away, all it takes is one photon to get to your eye to see it.