

Modern Atomic Theory

Electromagnetic Radiation and the Idea of Quantum

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By the beginning of the 20th century, scientists had come a long way to understanding the make up of atoms. Rutherford had showed us that the density of the atom was confined to the nucleus, that the majority of the mass of the atom was located in the nucleus. We knew the mass of the electron. We knew that the electron took up most of the volume of the atom, but when we tried to apply the same set of formulas that worked so well in understanding macroscopic bodies, such as the planets, those start to fail when we apply them to the atom. In the next 20 to 25 years, we would undergo, in fact, a fundamental change in science, a scientific revolution, with the birth of quantum mechanics.

Now, to get a sense of what quantum mechanics is, I want you to consider this. Suppose that I wanted to have exactly 3 grams of this sugar. Well, I could weigh out 3 grams and if I was patient about it, I could get very, very close. Supposed I wanted to have 3.000 grams, like maybe with a different balance, I'd be able to eventually get there. But if I went much further than that, then I'd run into a problem that each grain of sugar was a finite amount of mass. And so I could add one grain or another grain, but I couldn't easily add a half a grain. And so that would give me some problems in being very exact about the amount of mass that I had.

Now, sure, I could just grind up the sugar, I mean, you're no dummy. I could just make the particle size a lot smaller, but I'm going to be ultimately limited to the size of the molecule. I can add one sugar molecule and then another sugar molecule, but I can't break that molecule in half. If I did, I would have something other than sugar. I would no longer have sugar. So we tend to talk about that as mass being quantized. Quantized in the sense that it comes in discreet quanta of mass – 1 molecule, another molecule, another molecule. And again, these are indivisible units. If I do divide them up, break them into pieces, I have something else.

Now, we're reasonably comfortable with this notion of mass being quantized and at the beginning of the 20th century, we were very comfortable with that. But what about the notion that light and energy might be quantized? That seems pretty strange. Certainly back 100 years ago; that was a very foreign idea. We have this notion that you can have any arbitrary amount of light, that you can walk into a room, and turn on your dimmer, and adjust it to whatever level you want. But what if it turned out that the light, just like mass, was quantized, that there was some fundamental unit of light that was indivisible? That's what this unit's all about.

So before we go any further and get into quantum mechanics, let's talk about light in general and light as we understood it at the beginning of the 20th century. We have some notion of light as something that's emitted from a source like the light above that comes down. I register that light in my eye. It may be reflected off of my coffee cup and then I see in my eye the coffee cup through scattering light off the coffee cup. So we have a sense of light propagating through the atmosphere or through a vacuum. But what exactly is light?

Well, light turns out to be a combination of an electric and a magnetic field oscillating very rapidly as it's propagating through space. Now, we won't get into the details of this yet, but what's important for us right now to recognize is that light is, in fact, a wave and behaves according to the properties of waves.

So let's step one further step back and look at waves, like the waves you would have in water, for instance. We would characterize waves by a wavelength, the distance between one peak and the next, amplitude, how big that wave is, and a speed, how fast that wave propagates in a particular direction. Now, there's actually a fourth way we would characterize these waves, which is a product of these other ideas, and that is the frequency.

Now, to understand what we mean by frequency, again, let's look at a wave and have that wave be propagating. So it's moving in this direction, let's say. And let's suppose that you stand right here and you ask how long will it take for the next peak to come. Well, that would be the period of the wave. If we ask a different question, kind of the reverse question, and that is how many peaks would pass every unit of time, that's our notion of frequency. The number of cycles that the wave goes through every second.

Now, to get a better idea of just how frequency works and how it relates to wave length, I want you to consider for a moment two speeding trains. You can tell that I wasn't hired for my artistic merit. But let's suppose that we've got a train with very long cars and another train with very, very short cars. Again, we'll assume both trains are traveling the exact same speed, and we're going to stand at the station and watch these trains go by. And furthermore, we're going to count how many cars, I used to love to do this as a kid, count how many cars go by every minute.

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Well, you can see by my cartoon hopefully that if these both are traveling the same speed, far fewer cars of this train will go by than this train. We'll have many more cars passing in a unit of time. We'd say then that the frequency of cars passing for the upper train is much higher than the frequency of cars for the lower. That's a consequence of the length of the car, or the wavelength if we're talking about waves, being longer for the train down here. So once again, notice the relationship. Given constant speed of those two trains, the longer the wavelength, the slower or the lower the frequency. We can express that mathematically, and that is that the speed of a wave is a product of the frequency of the wave and the wavelength of the wave. And the speed of that wave, if we're talking about light, turns out to be a constant as long as we're in a vacuum where nothing's going to interfere with our light, that speed is $3.00 \times 10^8 \text{ m/s}$. And normally notice our units are going to meters per second for speed, and that would mean our frequency units are going to be per second, and our wavelength units are going to be in meters.

So again, this is the important relationship we need to keep track of. That there's a fundamental relationship between frequency, wavelength and speed of light, and that light travels the same speed no matter what kind of light it is.

So what then do we mean when we talk about blue light or green light or red light? What's the difference? The difference is the wavelength of red light is fundamentally different than the wavelength of blue light. I try to show in this cartoon here, red has a much longer wavelength than does blue light. Well, what does that tell you about frequency? Remember our relationship. As the wavelength gets larger, the frequency is going to become lower, right? And so although red has a much bigger wavelength, it has a much lower frequency.

Just for fun, let's see if I can make this point a little more clearly. I have a piece of cardboard here with a slit cut out of it, and I'm going to try my best, at least, to pass this slit along the red wavelength at a constant speed. And I'm going to count out for you every time we see a peak go by. Here we go. Peak, peak, peak, peak.

Now, look what happens when I do the same thing but with green light. The same speed. Peak, peak, peak, peak, peak, peak, peak, peak, peak, peak. I'm sounding like a bird, but you can imagine what's going to happen is I get into blue and violet light, that the frequency gets higher and higher and higher as we go to shorter wavelength. So, red, orange, green, blue, violet light that we perceive as these different colors, we're perceiving different wavelengths and therefore, we're perceiving different frequencies of light.

Well, what happens if we get below red light? What happens if we go to a longer wavelength? We get under red or infrared. We go into a type of light that is on different than red light, except that our eye no longer can perceive it. But it's there, we can perceive it by our hands feeling warm, the warmth coming from infrared radiation. So directly below the visible light, is infrared light at longer wavelengths and therefore, at lower frequencies. Correspondingly, we could go the other direction and ask what happens beyond the violet and we get into the ultra-violet? Light we no longer can see but, again, it's there. It's very damaging, in fact. We here about ultra-violet rays damaging skin and so forth. Ultra-violet radiation is no different than violet radiation except that the frequency is a bit higher and the wavelength correspondingly is a little bit shorter.

Well, we can take this one more step and ask what's beyond the infrared. As we introduce longer and longer wavelengths. We find that we get into microwaves, the same type of radiation that cooks your food in a microwave oven. If we go still longer wavelengths, we get into radio waves, the type of electromagnetic radiation that's responsible for carrying signals to your car. If we got the other direction in the electromagnetic spectrum, we get into beyond ultra violet x-rays, very, very high frequencies, very short wavelengths of light, and then ultimately gamma rays, extremely high energy light, quite capable of causing enormous amounts of damage if we absorb it, but fundamentally no different than visible light that we see except that the frequency is much, much higher and the wavelength correspondingly, is much shorter.

So finally, what's an example of a type of problem that you might be asked if you're studying for an exam? Let's suppose your microwave oven uses radiation with a frequency of 2.45×10^9 cycles per second, or hertz, you'll oftentimes hear that term as well. What's the wavelength of that radiation? Well, our fundamental relationship, again, is that the speed of light is a constant, and it's equal to the wavelength times the frequency. We know, in this case, the frequency, so rearranging our terms to solve for wavelength, and putting in numbers for the speed of light, 3×10^8 meters per second, and for the frequency we end up with a wavelength of .12 meters. Now, that's about 12 centimeters, about that big. So the radio waves, or I should say the radiation in a microwave oven actually has very large wavelengths. So if you've got a crack in your microwave oven between the door, for instance, and the rest of

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the oven, that's about a half an inch wide, don't worry about getting microwave radiation because, again, the radiation for microwaves and the wavelength is much, much bigger.

So what we've learned is that there's a fundamental relationship between frequency and wavelength, referring now to electromagnetic radiation, and what we perceive as light is actually visible light, the light that our eye can pick up, but that in fact, it's a small subset of the overall electromagnetic spectrum

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