Quantum Mechanics - Part 1: Crash Course Physics #43

Crash Course: Physics
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Shini: Here's a question that's plagued physicists for centuries. What exactly is light? When we talked about this earlier, we came to the conclusion that light is a wave.

Which it is. Or at least, light behaves like a wave, when you you use it in certain experiments. So for most of the 19th century, it seemed like the question had been settled. Physicists agreed: light is a wave.

Then, new discoveries made them start to question that. They started getting more and more clues that light could also behave like a particle. Which led to the strange concept that light was both a particle and a wave. This kickstarted the development of a little something you might have heard of, called quantum mechanics.

[Theme Music]

One of the most important clues that light had to be more than just a wave was what's known as the ultraviolet catastrophe. And that name isn't really an exaggeration – the ultraviolet catastrophe was disastrous for conventional thinking about the physics of light.

We've talked before about how objects radiate heat. Specifically, the amount of heat they radiate over time is proportional to their temperature raised to the fourth power. But there's more going on there than just heat. Objects actually radiate energy that covers a whole range of frequencies on the electromagnetic spectrum – all different kinds of light.

Now, there's this thing called a blackbody, which is basically the idealized version of a radiating object. No true blackbodies exist, but in theory, they absorb all incoming light without reflecting any, and radiate energy accordingly.

Not all of the energy coming from a blackbody has the same intensity. You can predict the intensity of the energy coming from a blackbody – or blackbody radiation – based on its temperature. But when physicists came up with an equation for this intensity, using the idea that light is a wave, they ran into a big problem.

The equation they came up with, known as the Rayleigh-Jeans law, predicted that the higher the frequency of the radiation – and therefore, the shorter the wavelength – the higher the intensity. And that matched up with experimental results really well but, only to a point. Once the frequency of light got into the ultraviolet range or higher, the Rayleigh-Jeans law didn't fit the results of experiments at all.

Instead, experiments showed that blackbodies had a peak intensity, based on their temperature. At a certain frequency, the light would be at its most intense, and after that, the intensity would actually drop as the frequency increased. The warmer the object, the higher the frequency of the peak intensity.

But there was always a peak. It wasn't supposed to be this way. Even worse, if you summed up the contributions of higher and higher frequencies to calculate the total power emitted by a blackbody, the Rayleigh-Jeans law predicted that you'd find infinite power. Which contradicts the principle of conservation of energy. This was the ultraviolet catastrophe.

Something was clearly wrong with the way physicists were thinking about light. As far as they knew, intensity was only supposed to keep getting stronger, as the frequency got higher. So, what were they missing? The catastrophe was resolved using an equation derived by German physicist Max Planck – an equation that basically led to the entire field of quantum mechanics.

The equation, known as Planck's law, was actually very simple, but the concept it was based on was very new. Planck's law says that electromagnetic energy takes the form of tiny, discrete packets, called quanta. In other words, at a certain point, you can't divide energy into anything smaller than these packets.

And the energy in each quantum is equal to the frequency of the light, times a very small number called Planck's constant, represented by the letter h. If you take Planck's law into account when you try to predict the intensity of blackbody radiation, you end up with an equation that predicts the experimental results perfectly, including those weird peak intensities. So, the ultraviolet catastrophe was resolved.

But now there was this whole new idea that had physicists rethinking everything: Energy could only exist in discrete packets: quanta. Before, physicists thought energy was a kind of continuous flow. But it turned out that at a certain point, you couldn't divide up energy into smaller amounts.

Our old friend Einstein played a big part in reworking physics using this new information – and he won a Nobel prize for it in 1921. Einstein argued that light energy traveled in packets we now call photons, which would essentially make light behave like a particle. Which was weird, because remember: there had been lots of experiments that showed that light behaved like a wave.

But Einstein suggested a way to prove whether light traveled in these discrete packets: an experiment involving the photoelectric effect. The photoelectric effect describes what happens when you shine a beam of light on a metal plate. Electrons leave the plate and hit a nearby collector, creating a current. Einstein realized that by studying the way the electrons left the plate, physicists could learn a lot about the properties of light.

Because, both the wave theory and the particle theory of light predict that light knocks electrons out of the metal. But each theory has a different explanation for why this happens – and different predictions when it comes to the details of the experiment.

Wave theory says that when a light wave hits an electron, it exerts a force on the electron that ejects it from the metal. According to this theory, if you increase the intensity of the light, you increase the strength of the electric field hitting the electrons. So you eject more electrons, and these electrons have a higher speed, and achieve a higher maximum kinetic energy, which is the kinetic energy of the fastest-moving electrons leaving the plate.

One important thing to note here is that according to wave theory, the frequency of the light shouldn't make a difference. Only the intensity matters. Particle theory, on the other hand, says that electrons get ejected from the metal when they're hit by individual photons.

The photon transfers its energy to the electron, which pops out of the metal. And the photon is destroyed in the process. But there's a minimum energy that the photon needs to transfer, in order to get the electron to overcome its attraction to the metal and pop out.

That minimum energy is called the work function, W_0. If the photon has less energy than the work function, the electron won't go anywhere. But if the photon has more energy than the work function, then some of the photon's energy will be used up to tear the electron away from the metal, and the rest will give the electron kinetic energy.

And some electrons will be more strongly attracted to the metal than others. But the electrons with the maximum kinetic energy will be the ones that took the bare minimum amount of energy to separate from the metal. So, according to particle theory, we can

say that the energy of the photon is equal to the work function, W_0, plus the maximum kinetic energy. And the energy of the photon is also equal to Planck's constant times the frequency.

This equation tells you that if you increase the frequency of the light, the maximum kinetic energy of the electrons should increase accordingly. And if you go below a certain frequency – f_0 – where Planck's constant times f_0 would be equal to the work function – then you're not going to eject any electrons at all.

This means that increasing the intensity of the light increases the number of electrons ejected, but it doesn't affect their maximum kinetic energy. So if you want to know whether the wave theory or the particle theory is right, all you have to do is try a few simple tests: Is there a cutoff frequency below which electrons aren't ejected from the metal, no matter how long you wait? What happens when you raise the frequency higher? And when you increase the intensity of the light, does that affect the maximum kinetic energy of the ejected electrons?

Turns out, there is a cutoff frequency, and the higher the frequency is above the cutoff, the higher the maximum kinetic energy is of the electrons. And sure enough, increasing the intensity of the light only affects the number of electrons ejected.

It doesn't change their maximum kinetic energy. The results of all these tests with the photoelectric effect match up with the predictions of the particle theory of light.

So, photons really exist. Light travels in discrete packets and behaves like a particle. But what about all those other experiments that showed light behaving like a wave?

Well, the thing is light can behave like both. In certain circumstances, it can behave like a particle. In others, it can behave like a wave. This is called the wave-particle duality.

When it comes to the physics of the very small, your intuitive understanding of the world just doesn't apply. You can't describe things like light using the concepts you're used to, that work on a larger scale. When you're trying to explain something totally outside the way you've directly experienced the world, you're going to run into some brain-bending physics.

And the discovery of Planck's law – along with the idea that light energy traveled as discrete packets – turned into the foundation for the concepts and equations that we use to analyze the behavior of the very small. And that field of physics, which studies how quanta behave, is what we call quantum mechanics.

Today, you learned about the ultraviolet catastrophe, and how it was resolved by Planck's law. We also talked about photons, and how the photoelectric effect proves the particle nature of light. Finally, we discussed the wave-particle duality.

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