Quantum Mechanics - Part 2: Crash Course Physics #44

Crash Course: Physics
https://youtube.com/watch?v=qO_W70VegbQ
https://nerdfighteria.info/v/qO_W70VegbQ

Shini: One of the strangest ideas ever proposed in physics was that light can be both a particle and a wave. And in 1923, a French physicist named Louis de Broglie proposed an even more radical extension of that idea: What if the wave-particle duality didn't just apply to light? What if it applied to basically everything?

What if all matter had a wave associated with it? Turns out, he was right. Applying the wave-particle duality to matter led to the development of a way to analyze the behavior of tiny particles more accurately than ever before.

And it also helps us understand that there are some things about the physics of the very small that we'll never be able to describe accurately. I'm talking about uncertainty. I'm talking about how a thing can be in more than one place at the same time. And, yes, I'm talking about a little cat in a box.

[Theme Music]

De Broglie was a big believer in the idea that there's symmetry in nature. His reasoning was that if light could behave like both a particle and a wave, then matter should do it too. What's more, the math seemed to work out. Light's momentum is equal to the Planck constant divided by the light's wavelength.

So according to de Broglie's proposal, the same equation would hold true for matter – meaning that you could find the wavelength of any bit of matter as long as you knew its momentum. The easiest way to test this was by using electrons.

Remember the double slit experiment? That was one of the key ways physicists showed that light can behave like a wave. When you shoot rays of light through two slits, they interfere with each other like waves, creating a certain, predictable pattern, known as a diffraction pattern, on a screen placed behind the slits.

To see if matter could also behave like a wave, physicists tried the same experiment, but with a beam of electrons instead of light. They shot this beam of electrons at a plate with two slits cut into it, with a screen behind the plate that glowed wherever it was hit by an electron. And they found that the electrons created a diffraction pattern, just like light did!

Meaning, the electrons were acting like waves and interfering with each other! This discovery was a really big deal. It showed that de Broglie was right – electrons do behave like both waves and particles. And so does all other matter – atoms, molecules, everything. So a ball flying through the air? That has a corresponding wavelength.

When you're driving your car down the highway, it has a wavelength. Even your body can have a wavelength. Which is just totally counter to the human experience of the universe. But that's quantum mechanics for you.

By now, you're probably wondering: if all objects can have wavelengths, why don't we see them? Well, remember: the wavelength is equal to Planck's constant divided by the momentum. But Planck's constant is a tiny number. And the larger the momentum, the tinier the wavelength. For anything that's big enough to see with the naked eye, the wavelength is so small that there's no way we'd ever be able to detect it.

Take a baseball with a mass of 0.2 kilograms, for example, flying through the air at 40.2 meters per second. The ball's wavelength is equal to Planck's constant divided by its momentum. And its momentum is equal to its mass times its velocity.

So, to find the ball's wavelength, you divide Planck's constant by the ball's mass times its velocity, which comes out to a wavelength of 8.24 x 10^-35 meters. In other words, to write out the fraction of a meter that the wavelength is equal to, you'd have to write down a decimal point, then 34 zeroes, then the numbers 824. Compare that to the radius of a hydrogen atom, which is about 2.5 x 10^-11 meters.

So the ball's wavelength is unimaginably small. We have no way to measure waves that tiny, so you can't see that your baseball is also a wave. But it is.

A lot of quantum mechanics has to do with the wave properties of matter – and probability. Let's take a look at the double slit experiment with electrons again. If you just let the electrons go through the slits slowly, it sort of looks like they're landing on the screen in random spots.

It's only after a while that you start to notice the diffraction pattern, because more electrons land in the spots that correspond to the bright bands in the pattern. That's because for electrons, and matter in general, probability is a huge factor in how they behave on the quantum level.

When quantum mechanics looks at the wave nature of matter, it's mostly concerned with the probability that particles, like electrons or even entire atoms or molecules, will be in certain places at certain times. That probability is predicted by the wavefunction, an equation that relates some of the properties of a quantum mechanical system, like an electron or atom.

The equation was developed by Austrian physicist Erwin Schrödinger in the 1920s. There's a lot of advanced calculus that goes into actually using Schrödinger's equation, but one of the main reasons the equation is useful is that you can use it to predict the probability of finding a particle at any given point in space, known as the probability density function.

You know those electron clouds you'll sometimes see in models of atoms? Those show the probability of finding the atom's electrons in the space around the nucleus. They're a graphical representation of the probability density function – meaning that the shapes of the clouds are calculated using Schrödinger's equation.

One of the most intense debates in quantum mechanics is about what it actually means for a particle to have a probability density function. Say you have an electron in a box. The electron's probability density function tells you that at a given moment, there's a certain probability that the electron will be in various locations in the box. But if you opened the box to check where the electron is, you'd see that it's only in one specific spot.

So, what does it mean that there's a probability of the electron being in a bunch of different places? Here's where quantum mechanics gets weird and counterintuitive again. Many physicists think that the electron is never in a specific place, at least not until you look at it. Instead, in a way it's in all these different places at once. But it's still just one electron. Then, once you observe or measure the electron in some way, it's only in one place.

Somehow, you measuring it forces the electron to be in one spot. The idea that a particle can be in more than one state at the same time is an example of quantum superposition, and it's the idea that Schrodinger was trying to explore in his famous thought experiment with the cat.

The thought experiment goes like this: You have a cat in a box, with a device that releases poison only when a radioactive atom decays. Quantum superposition says that as long as you don't know what state the atom is in – and therefore whether the poison has been

released – the cat is both alive and dead at the same time.

Schrodinger came up with this thought experiment as a way to demonstrate that the idea was ridiculous – and it IS ridiculous, but it's also probably accurate. It's just one of those things that's totally counter to the way we experience the world.

Now, let's say you do measure an electron. There's still going to be some uncertainty in that measurement, because of something called the Heisenberg Uncertainty Principle. This principle says that no matter how good your measuring instrument is, you can only know the position and momentum of a particle, like that electron in a box, up to a certain level of precision. After that, you could get a better measurement of your electron's position, but you'd have a much less precise measure of its momentum.

Likewise, you could get a better measurement of the electron's momentum, but then you'd have to sacrifice some knowledge of its position. Why? It has a lot to do with that whole wave versus particle thing.

Like we said earlier, a wave's momentum is just Planck's constant divided by its wavelength. So, if you're using the wavefunction to describe your electron as a wave, you can know its exact momentum. The problem is, that wave is spread out, with no exact position.

So by describing the electron in a way that allows you to measure its momentum, you lose the ability to measure its position. Now, you could try describing the electron as a particle and get its position that way, but then you'd have a similar problem: the equations involved wouldn't allow you to measure the electron's momentum.

So, quantum physicists try to make the best of both worlds by describing things like electrons using what's known as a wave packet – basically, a collection of waves all added together. They use Schrodinger's equation to calculate different waves that describe a quantum mechanical system, like that electron you've been trying to measure.

When all those different waves are added together, you can get some idea of the electron's position – but you also end up with some uncertainty when it comes to the electron's momentum. So there's a limit to how precisely you can measure position and momentum combined.

It turns out that there will always be an uncertainty that's at least equal to Planck's constant divided by 4 times pi. In a classical world, this uncertainty isn't that much of a big deal. If you're measuring the width of your desk, for example, the uncertainty is so tiny that it isn't going to matter.

When you're trying to measure tiny things like atoms or electrons, though, it can be a real problem. You can't always know an electron's position as precisely as you'd like, because then you'll have a less precise measurement of its momentum. So quantum mechanics tells us that there's a built-in limit to how much we can learn about particles.

When people say quantum mechanics is weird, they aren't kidding. The more you learn about quantum, the more weirdness you'll find. But it's still the best way to describe the behavior of very tiny things.

Today, you learned about how the wave-particle duality applies to matter. We also talked about Schrodinger's equation and the meaning of the probability density function. Finally, we covered the Heisenberg Uncertainty Principle.

Crash Course Physics is produced in association with PBS Digital Studios. You can head over to their channel to check out a playlist of their latest amazing shows, like: Art School, Indy America, and Shank's FX. This episode of Crash Course was filmed in the Doctor Cheryl C. Kinney Crash Course Studio with the help of these amazing people and our equally amazing graphics team, is Thought Cafe.