Quantum Mechanics

Transcript

http://quantumspotacademy.org/videos/quantum-mechanics/

If you don't believe that truth is stranger than fiction, then you haven't heard about quantum mechanics. Perhaps more than any other theory in physics, quantum mechanics overturns our common sense and reshapes our most basic assumptions about reality. Niels Bohr, one of the founders of the field, said that "If quantum mechanics hasn't profoundly shocked you, you haven't understood it yet." Prepare yourself for a profound shock, because we are about to dive into the phenomenally counterintuitive quantum realm.

We'll begin our exploration of quantum mechanics with a discussion of light. What is light made of? What gives it its unique properties? And, most importantly, what kind of experiment can we perform to find out?

Before quantum mechanics came along, there were two major theoretical models of light: the particle theory and the wave theory. Some people believed that light is composed of discrete particles, called photons. Others believed that it's a continuous wave like a ripple in a pond. Even though these two theories are very different, there is some extremely convincing evidence for both, so it's not at all obvious which one is correct.

Let's try to figure out whether light is made of particles or waves by performing a clever test called the double slit experiment. To perform this experiment, we need to shine a beam of light at a barrier with two very small slits in it. Then we will observe the light that passes through when it hits a photosensitive screen. Depending on what we see on the screen, we should be able to deduce whether light is made of particles or waves.

If the particle theory of light is correct, then the photons will only be able to pass through one slit or the other, and thus we would observe two vertical bars of scintillating points on the screen.

However, waves behave very differently. Most importantly, waves can interfere with each other. For example, if there are two ripples in a pond, the crests and troughs of the waves add together in some places, and cancel each other out in others, forming a characteristic pattern called an interference pattern. So if the wave theory of light is correct, then when the light waves reach the double slit, they will divide into two separate waves and then those two waves will interfere with each other. Because of the interaction of the two waves, we would expect to see a fuzzy interference pattern on the screen.

We have two different hypotheses for two different theories. Now all we have to do is run the experiment and see what happens! If we see two bars of scintillating points, then light is made of particles. If we see a fuzzy interference pattern, then light is made of waves!

When we run the experiment, this is what we see. Wow! This isn't what we were expecting at all! On the one hand, we can see individual particles hitting the screen, but on the other hand, we still see a wave-like interference pattern. These results are completely counter to our expectations because they contradict both the particle theory and the wave theory of light. Maybe something went wrong with our experiment. Maybe we made some sort of mistake. After all, common sense informs us that nothing behaves this way.

But in this case, there's no getting around the fact that our expectations were simply incorrect. When we are faced with surprising evidence, we have to suspend our "common sense" intuition and revisit our assumptions. The unusual results of the double slit experiment require that we create an entirely new set of physical laws and this new theory of physics is called quantum mechanics.

Quantum mechanics is dramatically different from classical physics that predated it. In quantum mechanics, light isn't a particle and it isn't a wave, but it does exhibit certain qualities of both particles and waves. This peculiar property is called wave-particle duality and, believe it or not, it doesn't only apply to light. All fundamental constituents of matter and energy obey wave-particle duality — that includes the protons, neutrons, and electrons that make up all atoms. So even things that we usually think of as discrete particles, like the atoms in your body, still exhibit wave-like properties.

Our everyday experience has led us to think in terms of either particles or waves, but neither of those concepts is completely consistent with our observations. Instead we need to create a radically different paradigm. We need to invent a new construct that will adequately describe the results from our experiments.

The construct that physicists have created is called a wavefunction. A wavefunction is a mathematical object that represents a physical system and it's usually written as the Greek letter ψ (psi). For example, you could write a wavefunction to describe a photon of light. Now it turns out that if you take the square modulus of the wavefunction (which is kind of like multiplying it by itself), you will obtain a probability distribution. This is where things get interesting. The probability distribution tells us how likely it is that we might find the photon at a given place, but it doesn't tell us exactly where the photon is. For example, the photon is probably here but probably not over there.

In classical physics, we might have asked, "is the photon here?" or "is the photon there?" But in quantum mechanics, those questions are meaningless. The only thing we can ask is, "what is the probability that we might find the photon here or there?" In this way quantum mechanics makes us think about reality in a dramatically different way. Instead of having a single location, a photon exists at all possible locations with different probabilities. To get a better understanding of this counterintuitive idea, let's return to the double slit experiment.

When a single photon of light is emitted from the light source, it doesn't follow a single path through one slit or the other. Instead, it passes through both slits at the same time. We say that it's in a superposition of two possible states. Then it interferes with itself causing an interference pattern. When it finally hits the screen, we see it in a single place, but because of its probability distribution, we are more likely to see it in some places than in others, which is what causes the interference pattern when we use many photons. Whew! The photon propagates like a wave through both slits and then we observe it like a particle on the other side.

This is partly what Niels Bohr meant when he said that quantum mechanics is profoundly shocking. At the quantum scale, we have to completely rethink even the most simple phenomena. But don't get too comfortable! We've only just scratched the surface. Let's perform the double slit experiment again, but this time we'll add a new measuring device, so that we can measure the photon as it passes through the two slits. Amazingly, with this simple change to the experiment, the interference pattern disappears. Suddenly, it looks like light is made of particles. What happened?

Remember that in the original experiment the photon passed through both slits in a superposition of two states. When we added the measuring device, it caused a fascinating process called wavefunction collapse. The photon's wavefunction collapsed so that it was no longer in a superposition of two states. It randomly selected either the left or the right slit and only passed through that one. That's why the interference pattern disappeared on the screen. The photon could no longer travel through both slits and interfere with itself because its wavefunctions collapsed halfway through.

But why did we collapse the wavefunction by measuring it? Why did the simple act of looking at the photon change the way it behaved? There are a number of different interpretations of quantum mechanics that are intended to make sense out of this result.

One explanation is the many worlds theory, which says that although we only perceive the photon passing through one slit, it also passes through the other in a parallel universe. But for now, these interpretations are philosophical speculations outside of the realm of physics.

Quantum mechanics has inspired a great deal of science fiction and pseudoscience, and it's easy to see why. The unusual predictions of quantum mechanics can easily be misinterpreted as magic or supernatural. It's important to remember that quantum mechanics really isn't any more mysterious than any other physical theory. It is nothing more than a mathematical model that we can use to make testable predictions. Nonetheless, it certainly takes some getting used to.

One of the most apparently paradoxical phenomena revealed by quantum mechanics is quantum entanglement. Quantum entanglement happens when a pair of particles is in a superposition of two states so that when we measure one particle, the wavefunction for the entire system collapses. By analogy, imagine that I have two boxes. Each holds a marble that's in a superposition of red and blue. If the marbles are entangled, then when I open one box, both marbles will collapse to a single color so that the two marbles always have opposite colors. It almost seems that the two marbles are instantaneously communicating with each other. The phenomenon of quantum entanglement is central to the concept of quantum computers, which have the potential to revolutionize computing if we can learn how to consistently manipulate these fragile entangled systems.

Another example of quantum strangeness is quantum tunneling. Imagine shooting an electron at a thin barrier. Using our everyday intuition, we would assume that the electron would bounce off of the barrier each time we tried this experiment. But quantum mechanics informs us that there is a small probability that the electron will actually appear on the other side of the barrier. This is called quantum tunneling, because it appears that the electron tunneled through to the other side. And quantum tunneling doesn't just apply to electrons! If you put a marble on a table-top, there is a very small probability that the marble will tunnel through the table and fall onto the floor below!

Now, wait a moment! If quantum mechanics is really true and all of these bizarre phenomena are really possible, then why don't we ever see any of these strange things happening? How can we reconcile quantum mechanics with our everyday experiences?

Well, it all comes down to a matter of scale. You see, in general, the larger the object, the less pronounced the quantum effects. A tiny particle like a photon or an electron is decidedly quantum, but larger objects tend to behave much more classically. Even a microscopic bacteria or virus is far too big to have noticeable quantum properties. The quantum effects are still there; they're just so small that we never notice them. So although it's possible that a marble will tunnel through a tabletop, it's so unimaginably unlikely that it's effectively impossible. That's also why you wouldn't see an interference pattern if you performed the double slit experiment with marbles instead of photons. Marbles are just too big to demonstrate quantum properties.

In other words, the laws of quantum mechanics model the way the world really works, but the laws of classical physics serve as an excellent approximation for things at the scale of everyday life. The reason that we don't use quantum mechanics to model things like marbles is that the tiny increase in precision comes at an immense computational price. It's a lot easier to just stick with our classical approximations for most things.

One of the most interesting features of quantum mechanics that we've discussed so far is its probabilistic nature. Quantum mechanics tells us that there are some things that are impossible to predict with certainty. For example, when we perform the double slit experiment, there is no way for us to predict with certainty exactly where we will observe a photon appear on the screen. We can only predict the probability distribution. Some people propose "hidden variable" theories that aim to put certainty back into fundamental physics, but so far none of them have been successful. By now most physicists agree that inherent probability is probably here to stay.

For hundreds of years, physicists have believed that the universe is deterministic. In other words, if we know the exact positions and velocities of every single particle in the entire universe, then using the laws of physics we should be able to predict with complete certainty the exact positions and velocities of all of those particles at any time in the future or past. But quantum mechanics adds a twist to determinism. Since particles don't have definite positions, we can't predict where a particle will be, but we can predict exactly how likely we are to find it in any given place. In a way, quantum mechanics is still deterministic, but we have to accept that we can't determine a particle's position; we can only determine its wavefunctions. This might be what Niels Bohr meant when he said that "everything we call real is made of things that cannot be regarded as real."

Quantum mechanics takes some getting used to at first, but it has been verified by countless experiments. Quantum mechanics explains how electrons orbit atomic nuclei and what color of light is emitted when a substance is heated, and how the sun produces energy. Quantum mechanics has been used to model chemical reactions with extraordinary precision and it's vital for designing modern electronics like cell phones. Indeed, quantum mechanics may be the most successful theory that physicists have ever developed. Its predictions match our observations so closely that it's now accepted as the true nature of the universe. Or at least, it's the best theory that we have so far. Someday quantum mechanics may be surpassed by an even better theory. In this sense, physics is an iterative process. Physicists are constantly refining the current theories to make them increasingly accurate.

But physics is also a creative endeavor. It takes considerable imagination and ingenuity to create a new mathematical model for the universe. The pioneers of quantum mechanics boldly rejected conventional wisdom and constructed a new theory of unprecedented accuracy. In addition to being amazing and perplexing, quantum mechanics is truly a crowning achievement of human intellect.