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8.01 Physics I: Classical Mechanics, Fall 1999
Transcript – Lecture 34

All physics of the 19th century and earlier is called classical physics.

Examples are Newtonian mechanics, which we dealt with this whole term, and electricity and magnetism, which you will encounter the next term.

In the early part of this century, when we learned about the composition of atoms, it became clear that classical physics did not work on the very small scale of the atoms.

The size of an atom is only ten to the minus ten meters.

If you take 250 million of them and you line them up, that's only one inch.

In 1911, the English physicist Rutherford demonstrated that almost all the mass of an atom is concentrated in an extreme small volume at the center of the atom.

We call that the nucleus, it's positively charged.

And there are electrons which are negatively charged, which are in orbits around the nucleus, and the typical distances from the nucleus to the electrons is about 100,000 times larger than the size of the nucleus itself.

As early as 1920, Rutherford named the proton, and Chadwick discovered the neutron in 1932, for which he received the Nobel Prize.

Now, let us imagine that this lecture hall is an atom.

And the size of an atom is defined by the orbits, the outer orbits of the electrons.

If I scale it properly, now, in this ratio 100,000 to 1, then the size of the nucleus would be even smaller than a grain of sand.

And it just so happens that yesterday I went to Plum Island, I walked for three hours on the beach and I ended up with some sand in my pockets.

And so I will donate to you one proton; make sure you hold onto it...

Ooh, this is two protons, that's too generous.

So keep it there--

this is one proton.

And there would be an electron, then, anywhere there, near the walls, going around like mad in orbit and that would then be a hydrogen atom.

Just think about what an atom is.

An atom is all vacuum.

You and I are all vacuum.

You think of yourself as being something, but we are nothing.

You can ask yourself the question, If you are all vacuum, why is it, then, that I can move my hand not through the other hand, like a ghost can walk through a wall? That's not so easy to answer, and in fact, you cannot answer it with classical physics and I will not return to that today.

But you are all vacuum.

According to Maxwell's equations, Maxwell's law of electricity and magnetism, an electron, because of the attractive force of the proton, would spiral into the proton in a minute fraction of a second, and so atoms could not exist.

Now, we know that's not true.

We know that atoms do exist.

And so that created a problem for physics and it was the Danish physicist Niels Bohr who in 1913 postulated that electrons move around the nucleus in well-defined orbits which are distinctly separated from each other, and that the spiraling-in of the electrons into the nucleus does not occur, for the reason that an electron cannot exist in between these allowed orbits.

It can jump from one orbit to another, but it cannot exist in between.

Now, Bohr's suggestion was earth-shaking, because it would also imply that a planet that goes around the sun cannot orbit the sun just at any distance.

You couldn't move it just a trifle in or a trifle farther out.

It would also require discrete orbits.

It would also mean that if you had a tennis ball and you would bounce the tennis ball up and down, that the tennis ball could not reach just any level above the ground, but it would only be discrete levels, and that is very much against our intuition.

We'd like to think that when you bounce a tennis ball, that it can reach any level that you want to.

You give it just a little bit more energy and it will go a little higher.

That, according to quantum mechanics, would not be possible.

Now, all this seems rather bizarre, as it goes against our daily experiences, but before we dismiss the idea of quantization--

see, the quantization comes in when you talk about discrete orbits--

you have to realize that the differences in the allowed heights of the tennis ball and the differences between the allowed orbits of the planets around the sun would be so infinitesimally small that we may never be able to measure it.

In other words, quantum mechanics really plays no role in our macroscopic world.

Now, atoms are very, very small compared to tennis balls, and the quantization effects are much larger in the sub-microscopic world of electrons and atoms than in our familiar world of baseballs, pots and pans, and planets.

So before we continue, I would like to repeat to you one of the cornerstones of quantum mechanics.

And it says that the electrons in atoms can only exist at well-defined energy levels--

think of them as being orbits--

around the nucleus, and they cannot exist in between.

Now, when I heat a substance, the electrons in the atoms can jump from inner orbits to allowed outer orbits, and when they do so, they can leave a hole, an opening, an empty space in the inner orbits.

But later on, they can fall back to fill that opening.

They can occupy that place again.

And when I keep heating this substance, there is some kind of a musical chair game going on.

The electrons will go to outer orbits, they may spend there some time and then they may fall to lower orbits, to inner orbits.

You see here a vase, a very precious vase, and when I pick up this vase, I have to do work.

I bring it further away from the center of the Earth.

Now, is that energy lost? No.

I could drop the vase, and it would pick up kinetic energy.

I will get that energy back.

Gravitational potential energy will be converted to kinetic energy.

It will crash to pieces, and it will generate some heat.

In fact, the breaking itself of this vase would take some energy.

In a similar way, the energy that you put into electrons when you bring them to outer orbits is retrieved when the electrons fall back.

So there is a parallel--

dropping this vase and getting your work back that I put in.

It wouldn't be a nice thing to do to this 500-year-old vase, but as far as I'm concerned, perfectly reasonable to do it with Ohanian, so we can let that go, and the energy will come out in the form of heat and also in the form of, perhaps, some noise.

When electrons fall from an outer orbit back to an inner orbit, it's not kinetic energy that is released, but it comes out often in the form of light, electromagnetic radiation.

Light has energy.

Einstein formulated that a light photon, the energy of a light photon, is h times the frequency, and h is Planck's constant--

named after Max Planck--

and h is about 6.6 times 10 to the minus 34 joule-seconds.

Now we've also seen in 8.01 that lambda, the wavelength of light, equals the speed of light divided by the frequency.

And so if I eliminate the frequency, I also can write that the energy of a light photon equals hc divided by lambda.

And so you see, the more energy there is available, the smaller the wavelength.

And the less energy there is available, the longer the wavelength.

And so if the jump from an outer orbit to an inner orbit is very high, then the wavelength will be shorter than when the jump is relatively small.

I can make you some kind of an energy diagram of these jumps.

And these are energy levels, so energy goes in this direction, but if you want to, you can think of these as the position of how far the electrons are away from the nucleus, if you like that, if it helps you, so this will be the electron that will be the closest to the nucleus.

So these would be allowed energy levels, allowed orbits.

And if this electron had jumped all the way here, then it could fall back at a later moment in time and the energy could be so much that you couldn't even see the light.

It could be ultraviolet, and this jump may still be ultraviolet, but now this jump, which is a little less energy, that may be in the blue part of our spectrum.

So we may see this as blue light.

And this one, which is a little less than this, this energy may generate, this jump may generate green light.

And the jump from here to here, which is even less, may generate red light.

And a jump from here to here, which is even less, may again be invisible, so this may be infrared.

And so as the electrons fall from outer orbits to inner orbits, you expect very discrete energies to come out, very discrete wavelengths, and these wavelengths that you would see correspond, then, to these allowed transitions between these energy levels.

So if we could look at that light and sort it out by color, we would, in a way, see these energy levels.

Now, you have in your little envelope a piece of plastic, which we call a grating, and the grating has the ability to decompose the light in colors, which we call a spectrum, and we're going to shortly use that grating to look at light from helium and light from neon.

But before we do that, I'd like to hand out--

as a souvenir to a few people, randomly picked--

something that they can also use.

It's not as good as your grating, though, but it's also nice.

You will see a more spectacular result, but not as clean.

It's not as clean.

All right, one for you, one for you, one for you and one for you.

And you want one--

I can tell that--

and you want one.

And here, for you, for you.

Oh, no, this side hasn't had anything.

I've got to walk all the way over now.

So this is really for children's parties, which I'm handing out.

Oh, George Costa, you want one, of course.

Professor Costa wants one--

I couldn't bypass him.

And you want one, okay, and you want one.

So, by all means, use your grating, but then, at the very end, you can always use these little spectacles, which don't work nearly as well, but, uh... this kind of thing.

I'm going to light here this bulb, this light, which has helium in it, and what you're going to see with your grating, if you hold your grating properly--

you may have to rotate it 90 degrees; you will see how that works when you try it--

you're going to see very, very sharp, narrow lines at various colors.

I want you to realize that the reason why you see very sharp, narrow lines is only because my light source are very sharp, narrow line.

If you use it on something that is not a very sharp, narrow line, then you're not going to see through that grating very sharp, narrow lines.

So don't confuse the lines that are on the grating with the line source that I have here.

Now, when you look through your grating very shortly, you will see, on both sides, the wonderful lines.

It's a mirror image, and we will discuss it in a little bit more detail, but before you look through your grating, I first want you to simply look at it without the grating, because then it is even more spectacular when you use the grating.

Because you have no clue, when you don't use the grating, what kind of colors are hidden there.

And the colors that you are going to see are these electron levels.

So I am going to make it dark.

And I will turn this on.

And this one, I believe, is helium.

I have a grating here.

So we have to rotate it so that you see vertical lines on either side.

You may have to rotate it 90 degrees, no more.

And if you look closely--

for instance, look on the right side of the light--

you'll see a distinct blue line, a few blue lines, green, very nice bright yellow one, and you see red.

And if you go further to the right, you see a repeat.

It's a little fainter, but you see a repeat of that.

That's not important right now; I just want you to see that this light, which you have no idea that it comes out in very discrete wavelengths, very discrete frequencies, and they correspond to these jumps from allowed energy levels to other allowed energy levels, but there is nothing in between.

And when you look on the left side, you'll see a mirror image of what you see on the right side.

Now, neon... excuse me, helium has only two electrons.

I'm now going to put in the neon bulb and that makes it richer, for reasons that neon has ten electrons, so you have many more orbits, so many more ways that the electrons can play musical chair.

A lot of lines in the red--

I'm not blocking you, I hope--

a lot of lines in the red, and some beautiful lines in the yellow.

I see some in the green, I don't see much in the blue...

a little bit in the blue.

But the key thing is, I want you to see that these lines are discrete.

It is not just any wavelength that can be generated; it's only the allowed orbits, the musical game when the electrons jump from one orbit to another, and that gives you this unique discrete spectrum.

Now, these light spectra were known long before Bohr came with his daring ideas, but before quantum mechanics, these lines were a great mystery, but they no longer are.

I suggest you use this grating and use it when you are outside at night; look at some streetlights, particularly sodium lamps and mercury lamps.

And, of course, the neon lamps are quite spectacular, but keep in mind, you will not see very nice straight lines unless your light source itself is a very nice straight, narrow light source.

Now, quantum mechanics took a big leap in the '20s, and it would be impossible for me in the available amount of time to do justice to all the basic concepts.

However, I will discuss some consequences that are rather nonintuitive.

Prior to quantum mechanics, there was a long-standing battle between physicists whether light consists of particles or whether they are waves.

Newton believed strongly that they're particles, and the Dutchman Huygens believed that they were waves.

And it seemed like, in 1801, that a conclusive experiment was done by Young, which demonstrated unambiguously that light was waves; Huygens was right.

But as time went on, discomfort was growing, as there were also experiments that showed rather conclusively that light really was particles.

And it was one of the great victories of quantum mechanics that it showed that light is both.

At times it behaves like waves and at other times, it behaves like particles; it all depends on how you do your experiment.

In 1923, Louis de Broglie made the daring suggestion that a particle can behave like a wave, and he specified, he was very specific, that the wavelength--

which nowadays is called de Broglie wavelength--

is h, Max Planck's constant, divided by the momentum of that particle and the momentum is the mass of the particle times the velocity, as we have seen in 8.01.

If the momentum is higher, then the wavelength is shorter.

A baseball will have a very high momentum, with a ridiculously low...

short wavelength.

Now, one of the startling consequences is that protons and electrons, which everyone of that time considered particles, can then also be considered as being waves.

And in 1926, the Austrian physicist Schrodinger drove the nail in the coffin with his famous equation--

Schrodinger's equation, it's called now--

which is the ground pillar of quantum mechanics and it unifies the wave and the particle character of matter.

Returning to my baseball, take a mass of the baseball of, say, half a kilogram and give it a speed of 100 miles per hour.

Calculate the wavelength that you would find, according to quantum mechanics.

That wavelength is so absurdly small, it is 20 orders of magnitude smaller than the radius of an electron, so it is completely meaningless.

So quantum mechanics plays no role in our macroscopic world of pots and pans and baseballs.

But now take an electron.

You take the mass of the electron, 10 to the minus 30 kilograms.

And you give the electron a speed of, say, 1,000 meters per second.

Now you get a wavelength which is comparable to the wavelength of visible light, red light.

And now it's something that becomes very meaningful, something that can be measured.

Now, you may argue, "Gee, what difference does it make? "Who cares whether something is a wave or whether something is a particle?" Well, it makes a huge difference, because waves have crests and they have valleys, and so if you take two sources of waves, either water waves--

two sources, tapping up and down on the water--

or you can take two sound sources, then there are certain locations on the surface of the water where the crest of one wave arrives at the same time as the valley of the other, and so they cancel each other out.

There is nothing, there is no motion of the water.

We call that destructive interference.

Of course, there are other places where there is constructive interference, where they support each other.

Now, if particles can do that, too...

That is very hard to imagine--

how can one particle with another particle interfere and vanish, that the two particles no longer exist? So if, indeed, particles are waves, you should be able to demonstrate that by having the interference pattern of two particles, like the water waves, and make--

at certain locations in space--

those particles disappear, which turn out to be possible.

But that's a very nonintuitive idea.

So we think of it too classically when we say, "Well, two particles cannot disappear." But in quantum mechanics, you can think in waves if you want to, and then you have no problems with the interference pattern and the destructive interference at certain locations.

Now, there are other remarkable consequences of quantum mechanics in classical mechanics.

If you and I are clever enough, you think that we should be able to determine the position of an object to any accuracy that we require, and at the same time determine also its momentum at any accuracy that we require.

It's just a matter of how clever we are.

Simultaneously, the object is right there and that is its mass and that is its speed.

However, the German physicist Heisenberg realized in 1927 that a consequence of quantum mechanics is that this is not possible.

Strange as it may sound to you, Heisenberg stated that the position and the momentum of an object cannot be measured very accurately at the same time.

And I will read to you Heisenberg's uncertainty principle, the way we know it.

It says, "The very concept of exact position of an object "and its exact momentum, together, have no meaning in nature." It's a profound nonclassical idea, and it is hard for any one of us--

you and me included--

to comprehend.

But it is consistent with all experiments that we can do to date.

I want to repeat it, because it's going to be important of what follows.

"The very concept of exact position of an object "and its exact momentum, together, have no meaning in nature." What does it mean? First, let me write down Heisenberg's uncertainty principle.

Delta p, which is the uncertainty in the momentum, multiplied by delta x, which is an uncertainty in the position of that particle, is larger or approximately equal to Planck's constant divided by two pi--

for which, in physics, we call that "h-bar"--

and h-bar is approximately 10 to the minus 34 joule-seconds.

You see, h is 6.6 times 10 to the minus 34.

If you divide that by two pi, you get about 10 to the minus 34.

What does this mean, now? What it means that if the position is known to an accuracy delta x--

we'll give you some examples--

that the momentum is ill- determined, is not determined, to the amount delta p, larger or equal than h-bar divided by delta x.

That's what it means.

And I'll give you an example which I've chosen from a book of George Gamow.

Gamow wrote a book which he called Mr. Tompkins in Wonderland. It's about dreams.

Mr. Tompkins wants to understand the quantum world, and there is a professor--

you will see a picture of the professor--

who takes him, in his dreams, along the various remarkable nonintuitive effects of quantum mechanics.

And in one of these dreams, the professor suggests that we make h-bar one.

And the professor takes a triangle in the pool table and he puts the triangle over one billiard ball, so the billiard ball is constrained in its position and that delta x is roughly...

say, 30 centimeters, 0.3 meters.

That means that the momentum is not determined, not determined to an approximate value of one divided by 0.3, is about 3 kilogram-meters per second.

Now, if we give the billiard ball a mass of one kilogram, then delta p is m delta v, and so if m is one kilogram, then the speed of that billiard ball is undetermined, according to Heisenberg's uncertainty principle, by at least approximately three meters per second.

Three meters per second--

that means seven miles per hour, and so that billiard ball will go around like crazy in that triangle, and that's exactly what happens in the dream.

And I will show you here a picture from that book.

Mr. Tompkins is always in pajamas, just to remind you that it is a dream.

And needless to say, the professor is a very old man and has a very nice beard; it adds to the prestige.

And I will read you from this book.

I will read you a very short paragraph that deals with this.

"So the professor says, "'Look, here, I'm going to put definite limits "'on the position of this ball by putting it inside a wooden triangle.'" "As soon as the ball was placed in the enclosure, "of the whole inside of the triangle "became filled up with glittering of ivory.

"'You see,' said the professor, "'I defined the position of the ball "'to the extent of the dimensions of the triangle.

"'This results in considerable uncertainty in the velocity "'and the ball is moving rapidly inside the boundary.

"'Can't you stop it?' asked Mr. Tompkins.

"'No, it is physically impossible.

"'Anybody in an enclosed space possesses a certain motion.

"'We physicists call it zero point motion, "'such as, for example, the motion of electrons in any atom.'" So here you see quantum mechanics at work when h-bar is one.

This is a very nonclassical idea, because you and I would think--

and we've always dealt with that in 8.01--

that you can take an object and place it at location "a," and we say at time t zero it is at "a" and it has no speed and we know the mass, so we know both the momentum and the position to an infinite accuracy.

But according to quantum mechanics, that's not possible.

So let's now return to the real world, where h-bar is not one, but where h-bar is 10 to the minus 34, and let's now put a billiard ball inside this triangle.

Now, delta x is the same, but since h-bar is 10 to the minus 34, delta p is, of course, 10 to the 34 times smaller, and so the velocity is 10 to the 34 times smaller.

This undeterminedness...

degree to which the velocity is now undetermined, is so ridiculously small--

it is 3 times 10 to the minus 34 meters per second--

that if you allowed that ball to move with that speed, in 100 billion years, it would move only 1/100 of a diameter of an electron, so it's meaningless again.

And so again, you see that quantum mechanics plays no role in our daily macroscopic world of baseballs and basketballs and billiards and pots and pans.

And therefore, it is completely okay for us to say, "I have a billiard ball which is at point 'a,' and its mass is one kilogram and it has no speed." That is completely kosher, completely acceptable, and quantum mechanics has no problems with that.

Let's now turn to an atom.

Take a hydrogen atom.

The diameter of a hydrogen atom is about 10 to the minus 10 meters.

So the electron is confined to a delta x of about 10 to the minus 10 meters.

That means the momentum of that electron becomes undetermined--

according to Heisenberg's uncertainty principle--

to about 10 to the minus 34, divided by 10 to the minus 10, is about 10 to the minus 24 kilogram-meters per second.

What is the mass of an electron? That's about 10 to the minus 30 kilograms.

So this, delta p, is also m delta v.

So it means that delta v--

that means the velocity of the electron--

is undetermined, according to Heisenberg's principle, by an amount which is at least 10 to the minus 24, which is this delta p divided by the mass of the electron, which is 10 to the minus 30.

And that is about 10 to the six meters per second--

that is one-third of a percent of the speed of light.

So the electron is moving only because of the fact that it is confined.

That's what quantum mechanics is all about.

The electron's motion is dictated exclusively by quantum mechanics.

I'm going to show you an experiment in which I want to convey to you how nonintuitive Heisenberg's uncertainty principle is.

I have here a laser beam, and this laser beam is going to be aimed through a narrow slit--

I'll make a drawing, I'll turn this light off--

and that slit, which is a vertical slit, can be made narrow and can be made wider.

Here is this light beam and here is this opening, this slit.

It's only going to be confined in this direction, not in this direction.

And so the light will come out here, and then, on a screen, which is going to be that screen, at large distance capital L, we're going to see that light spot, due to the light beam going through the slit and this separation, capital L.

I start off with the slit all the way open and so you're going to see this light spot like this.

And then I'm going to make the slit narrower and narrower, and as I'm going to cut into the light beam, what you're going to see is exactly what you expect.

You expect that this light disappears, and when I cut in further, you see exactly what you expect, that this light disappears.

And so the light spot there on that screen will become narrower and narrower and narrower.

But then there comes a point that Heisenberg says, "Uh-uh, careful now, because your delta x, your knowledge, "the accuracy in this direction where the light goes through "is now so high that now I'm going to introduce "an uncertainty in the momentum of that light.

"The momentum of that light is now no longer determined to infinite accuracy." And what that means, if you start fooling around with the momentum of that light in the x direction, it no longer goes through straight but it goes off at an angle, and I will make you a more quantitative calculation for that.

So let's look at this slit from above.

Here's the slit, and the slit has an opening, delta x.

And this delta x we're going to make smaller and smaller, and let us start with a delta x of about 1/10 of a millimeter, which is 10 to the minus 4 meters.

I have light, I know the wavelength of the light, and I know that lambda equals h divided by p, according to De Broglie.

I know the wavelength, I know h, and so I can calculate the momentum of that light.

I have done that, take my word for it.

It is about 10 to the minus 27 kilogram-meters per second.

That's the momentum of the individual light photons.

Think of them as particles, which you can do, according to de Broglie.

So now I have a delta p, the degree to which the momentum is undetermined, according to Heisenberg, is going to be 10 to the minus 34 divided by delta x--

which is 10 to the minus 4, so that is 10 to the minus 30, very small.

But the momentum itself is 10 to the minus 27, so it's only one part in a thousand.

So what will happen? If the light comes through here...

And I now make a classical argument.

I say, "This is the momentum of the light as it comes straight in." When it has to be squeezed through this narrow opening, Heisenberg's uncertainty principle demands that it is going to be undetermined, the momentum in this direction by roughly 10 to the minus 30, or more.

Remember, it is always larger or equal.

In other words, if I introduce, for instance, in this direction or in this direction, delta p, then I would expect that some of that light goes off in this direction.

It is this change in momentum, this undeterminedness in momentum, that makes it go off at an angle, only in the x direction.

If I have the slit like this, don't expect this to happen in this direction, because the uncertainty in the y direction, that's not the problem.

Delta y is not very small, it's delta x that is very small, so it's this direction that's going to give you trouble.

It's only in this direction that you know precisely where that light goes through.

This direction is not the issue.

So this angle theta can now be calculated very roughly.

Theta is obviously delta p divided by p, so theta is very roughly 10 to the minus 3 radians, which is a fifteenth of a degree, and if you have at a distance L--

if this distance here is L--

if you have here a screen, then the spot on this screen...

if I call that x at location L, then x at location L is obviously theta times L.

And if theta is 10 to the minus 3--

and let's assume this is about 10 meters away from us, so L is about 10 meters--

then you get 10 to the minus 2 meters.

That is one centimeter.

One centimeter in this direction and one centimeter in that direction--

two centimeters.

But when I make the slit width 10 times smaller, if I make the slit width only 1/100 of a millimeter, then this becomes 10 centimeters, because now I know delta x 10 times better, and so delta p is 10 times more uncertain.

So now I expect to see here at least a smear of 20 centimeters and at least a smear of 20 centimeters there.

So the absurdity is that a teeny-weeny little light source which in the beginning you will see as a very small spot...

When I make this slit narrower and narrower, indeed, you will see that you will lose photons, and you will see this getting narrower and narrower, and then all of a sudden, it begins to spread out, and it begins to spread out, and by the time I'm close to a tenth of a millimeter, the light spot will be yay big.

Very nonintuitive.

You make the slit smaller, and the photons spread out.

And I want to show that to you now.

I have to make it very dark.

And I need my flashlight, turn on the laser beam.

There you see it.

The slit is now all the way open.

Yeah, it's all the way open, and I'm going to close the slit now slowly.

And if you look closely, you will see that the...

Let me also get my red laser, then I can point something out.

You will see that the light will get squeezed in the horizontal direction.

You can see already at the left side, has a very sharp vertical cut-off, and the right side also.

It's getting narrower, it's getting narrower.

Getting narrower, but I'm nowhere nearly a tenth of a millimeter yet.

It's getting clearly narrower.

You see, it's getting narrower, it's getting narrower.

If I look here...

oh, I'm not yet at the tenth of a millimeter, but I'm getting there.

I'm going slowly, squeezing it.

I'm squeezing those photons.

Those photons now are forced to go through an extremely narrow opening and Heisenberg is very shortly going to jump in and says, "You are going to pay a price for that.

"You know too well where those photons are in the x direction.

"The price you pay--

"that nature will now make the momentum undetermined in the x direction." And you begin to...

you see it now.

You really begin to see that the center portion is widening.

Even photons appear.

Here, you see some dark lines, which I will not further discuss today, but notice that the light is spreading.

Of course, when I squeeze this slit, when I make it narrower, it's obvious that I lose light, because the light that hits the side of the slit is not going through, so the light intensity will go down.

That's just inevitable.

I used fewer photons.

But look at this.

There are photons here, there are photons there.

It's at least 10 centimeters, this portion.

From here to here is at least one foot.

I squeeze more--

this is more than half a meter now.

I squeeze more--

this is about one meter already.

I squeeze even more.

I close the slit now, and I will open it slowly.

I'm opening it very slowly, and at the moment that it opens...

Look at this! You see this? You see this wonderful streak? It looks more like a comet.

From here to here is at least a meter.

That's that center portion of the light.

It has spread out, since the poor light was forced to go through this very narrow opening.

Now I'm opening it more and more.

I'm opening it more, and now, of course, the reverse is happening.

Extremely nonintuitive.

Now, not only have you seen quantum mechanics at work, in terms of electrons jumping between orbits, but you now have also seen one other very interesting consequence of quantum mechanics, which is Heisenberg's uncertainty principle.

Now, the spreading of this light can very easily be explained without Heisenberg's uncertainty principle.

In fact, it was known, even in the previous century, to a high degree of accuracy, why this happens, and the dark lines were very accurately explained.

All I wanted to show is that the spreading of the light is entirely consistent with Heisenberg's uncertainty principle, and it better be, because it would not be possible, it would be inconceivable that you could do any experiment that would violate Heisenberg's uncertainty principle.

And if this light that you would see on the screen there, if that light spot would get narrower and narrower and narrower and narrower all the time, as we would think classically, that would have been a violation of Heisenberg's uncertainty principle, and that is not possible.

Now, there is no way in advance to predict which photons end up where.

All you can do with quantum mechanics is to do the experiment with lots of photons and then you will get a certain distribution and the distribution will be exactly as you saw there.

Quantum mechanics can never predict, on an individual photon, where it will end up.

We saw that bright spot in the center.

So if you did this experiment with one photon per day--

one photon per day going through this slit--

and you had a photographic plate there, and you would keep it there for months, and you would develop it, you would see the same pattern that you see there.

This photon arrives today.

Here arrives one tomorrow.

Here arrives one the day after tomorrow.

Here one the day after that, the day after that, the day after that, the day after that, the day after that, the day after that, and slowly are you beginning to see that pattern that you saw.

So don't think that this interference pattern that you saw is the result of two photons going through the slit simultaneously--

not at all.

You can do it with one photon at a time and you would see exactly the same thing.

Now, this idea--

that you cannot in advance predict what a particular photon will do--

is a very nonclassic idea, and it rubs us all the wrong way because our classical way of thinking is--

and you are no different from my own feeling in this respect--

that if you do an experiment a hundred times in a controlled way, you should get a hundred times exactly the same result.

Not so, says quantum mechanics.

All that quantum mechanics will tell you is what the probability is that something will happen.

No guarantees, but it is very good in predicting probabilities.

Now, Einstein had great problems with this idea of not knowing precisely what would happen, and he had endless discussions with Bohr and others in which he tried to convince them that because you couldn't predict what happened, that something had to be wrong with quantum mechanics, and Einstein's famous words were, "God does not throw dice." This was the way, was his way of saying, "It is ridiculous that the outcome of a well-controlled experiment is uncertain." Now, almost nine decades have gone by since the beginning of quantum mechanics, and we now know that God--

if there is one--

does throw dice.

However, God is bound to the rules of quantum mechanics and cannot violate Heisenberg's uncertainty principle.

The light could not go straight through without spreading when I made the slit as narrow as I did.

So quantum mechanics is a bizarre world that we rarely experience in our daily lives, because we are used to basketballs, baseballs, tennis balls.

But yet it is the way the world ticks, and atoms and molecules can only exist because of quantum mechanics.

That means you and I can only exist because of quantum mechanics.

I hope that this will give you something to think about, but I warn you in advance, because if you start thinking about this, it will give you headaches and it will give you sleepless nights.

And it has given me countless sleepless nights in the past, and even today, when I think about the consequences--

the bizarre consequences of quantum mechanics--

I still cannot comprehend it, I still cannot digest it and I still have headaches and sleepless nights.

But it may be necessary to go through these sleepless nights if you want to eventually evolve as an independent thinking scientist, and I hope that someday all of you will.

Thank you.

[class applauds]