PROFESSOR: So we're building this story. We had the photoelectric effect. But at this moment, Einstein, in the same year that he was talking about general relativity, he came back to the photon. And there there's actually a quote of Einstein's saying, his greatest discoveries, for sure, were special relativity and general relativity. The photo-- he got the Nobel Prize for the photoelectric effect, and he certainly helped invent the quantum theory and many important things in this subject, but in retrospect, his greatest successes were that. But he may have not quite seen it exactly that way. He wrote, that some stage of his whole life had been a difficult struggle against the quantum, pulsed by some small happy interludes of some other discoveries. But the quantum theory certainly made him very-- well, he was very suspicious about the truth, the deep truth of the quantum theory.

So 1916, he is busy with general relativity, but then he's more ready to admit that the photon is a particle, because he adds that the photon now has momentum as well. So it's a-- these photons that were not called photons yet are quanta for energy. But now he adds it's also for momentum. So this already characterizes particles. You see, there is the relativistic relation, well known by then, that e squared minus p squared c squared is equal to m squared c to the fourth.

You might say, well, this is a little surprising. And If you don't remember too much special relativity, this may not quite be your favorite formula. Your favorite formulas might be that the energy is mc squared divided by 1 minus v squared over c squared. And that the momentum is the ordinary momentum again multiplied by this denominator like this. But these two equations, with a little bit of algebra, yield this equation, which summarizes something about a particle, that basically if you know the energy and the momentum of a particle, you know its mass.

And it comes out from this. This is the relativistic version of similar equations in which you have energy one half mv squared, momentum, mv, and then energy equal p squared over 2m, a very important relation that you can check. For out of these two comes this one. And this is nonrelativistic. So for photons, we will have particles of zero mass. Photons have zero mass, m of the photon equals zero, and therefore e is equal to pc for a photon.

So we can look at what the photon momentum is, for example photon momentum. We can treat it as some particle and the photon momentum would be e of the photon divided by c, or h

Nu of the photon divided by c. And it's h over lambda of the photon of gamma. So this is a very interesting relation between the momentum of the photon and the wavelength of photons.

So the idea that the photon is really a particle is starting to gather evidence, but people were not convinced about it until Compton did his work. So the same Compton that we used this length over there, he works on this problem and does the following. So is Compton scattering, the name of the work. Compton Scattering.

So what is Compton scattering? It is x-rays shining on atoms again, but this time, these are very energetic photons, energetic x-rays. X-rays can have anything from a hundred EV to 100kEV, 100,000 electron volts. And what are the energies, of binding energies of electrons in atoms? 10 EV, 13 EV for hydrogen. So you're talking about 100,000 EV coming in, so it's easily going to shake electrons and release them very easily.

So you're going to have almost-- even though you're shining on electrons that are bound to atoms, it's almost like shining light on free electrons if it's x-rays. So a few things happening. So this is photons scattering on electrons. Scattering on electrons that are virtually free. And the first thing that happens is that there is a violation of what was called the classical Thomson scattering, that you may have started in 802.

So the reason Compton scattering did the job and physicists finally admitted the photon was a particle is that it made it look like particle collision of a photon with an electron, it could calculate and measure and treat the photon as a particle, just like another particle like the electron, and out came the right result. So the classical Thomson scattering was a photon as a wave.

And what does that do? Well, you have a free electron, and here comes an electromagnetic wave, E and B. And if it's low frequency wave, low energy electron, this electric-- the magnetic field does very little, because this election doesn't move too fast and the velocity is being small, the Lorentz force is very small. But the electric field shakes the electron. And as the electron is being shaken, it's accelerating, and therefore it radiates itself. And it radiates in a pattern, so you get photons out.

And the pattern is the following. I'll write the formula with this cross-section. We'll maybe not explain too much about what this cross-section means, it could be a nice thing for recitation. This is the formula for the Thomson cross-section as a function of the angle between the incident direction of the photon and the photon that emerges. So you detect photons out and this is the cross-section. What does it mean, cross-section? Well this has units. I will say, very briefly, units of area. Area per solid angle, but solid angle has no units.

So if you imagine a little solid angle here and you multiply by this cross-section, it gives you some area that represents the solid angle you're looking at to see how many photons you get. And the solid angle that you have multiplied here to give you an area, the area should be thought of as the area that captures from the incoming beam the energy that is being sent into this solid angle. So it represents an area, and an area represents an energy, because if you have a beam coming in from a magnetic wave through a little area, some energy goes in.

So that area that you get is that area that extracts from the incident beam the energy that you need to go in this solid angle direction. So basically, this is a plot of intensity of the radiation as a function of angle. But the most important thing, not only-- this is not quite accurate when the photon is of high energy. The thing that is pretty wrong about this is that the outgoing photon or wave has the same frequency as the original wave.

So that's a property of this scattering. The electron is being moved at the frequency of the electric field, and therefore the frequency of the radiation is the same. And this is all classical. But out comes, when you have a high energy, this thing is not accurate, and you have a different result. So what did Compton find? Well, the first thing is a couple of observations. . Treat the photon as a particle.

OK, so it has some energy and some momentum. The electron has some energy and momentum. You should analyze the collision using energy and momentum conservation. So before the collision, you have an incoming photon that has some energy and some momentum, and you have an electron, maybe here. And then after a while, the electron flies away in some direction, E minus. And the photon also, a photon prime of different frequency flies away. It's like a collision. You can do this calculation and maybe it could even be done in recitation. It's a relativistic calculation.

You were asked in first homework to show that the photon can not be absorbed by the electron, and that uses the relativistic relations if you want to show you just can't absorb it. It's not consistent with energy and momentum conservation. So it's something you can try to figure out. The other thing that should become obvious is that the photon is going to lose some energy, because as it hits the electron, it gives the electron a kick. The electron now has kinetic energy. Think of this in the lab. The electron was static, the photon was coming. After a while, the electron has moved, it's moving now with some velocity. The photon must have lost some energy. So photon loses energy. And therefore, the final lambda must be bigger than the initial lambda. Remember the shorter the wavelength, the more energetic the photon is.

So what is the difference? That's the result of a calculation. It's a nice calculation, all of you should do it. It's probably in some book, in many books. And it's a nice exercise also for recitation. Lambda final minus lambda initial. Or I'll write it differently. Lambda final is equal to lambda initial plus something that depends on the angle theta, in fact, has a one minus cosine theta dependence. But here has to be something with units of length

And the only party you have here is the electron. And this electron has some length, which is the quantum wavelength, which is very natural for a Compton scattering problem, of course. And it's here, h over mec. So the l Compton of the electron. And that's the correct formula for the loss of energy, or change in frequency. So the most you can get is if you don't interact when theta is equal to zero, the photon keeps going, doesn't even kick the electron. And then you get zero, the initial lambda is equal to the final lambda. But this can be as large as two, for totally backwords photon emitted. So theta equals pi, cosine pi is minus 1, you get 2. At 90 degrees, you get the Compton shift. So it's a very nice thing, you even know already what's happening here.

So let's describe the experiment itself, of how it was done. So he used, Compton, the experiment have a source of molybdenum x-rays that have lambda equals 0.0709 nanometers. So smaller than nanometers, it's 70 picometers. And that corresponds to e photon-- that's pretty small, so it must be high energy-- and it's 17.49 kEV. That's very big energy. And there was a carbon foil here. And you send the photons in this direction. And they were observed at several degrees, but in particular, I'll show you a plot of how it looked for theta equal 90 degrees, so detector.

So source comes in, carbon is there, and what do you get? You get the following plot. Intensity-- so you plot the intensity of the photons that you detect, as a function of the wavelength of the photons that you get, because there's supposed to be a wavelength, a shift of wavelength. So it's actually quite revealing, because you get something like this. A bump and a bigger bump here. Something like that. Pretty surprising, I think, to first approximation.

And here is about-- the first bump happens to have about the same wavelength as the incoming radiation, 0.0709. I should write it a little more to the left. 0.0709 nanometers over here. And then there is another peak at lambda f, about 0.0731 nanometers.

And the question is, what is the interpretation? Why are there two peaks and what's going on? Anybody has any idea? Let me ask a simpler question. Which is the lambda that corresponds to the prediction of the fact that the wavelength must change, the smaller one or the bigger one? The bigger one. You certainly should loose energy, so the lambda f, the thing we were expecting to see, presumably that thing, because we were expecting to see that at 90 degrees, the photons have this thing.

So we seem to observe this one. And let's look at it in a little more detail. You have this 0.0731 nanometers and you have the original light was at 0.0709 nanometers. So the difference is 0.0022 nanometers, which is 10 to the minus 9, but it's exactly, or pretty close, to this thing, because a picometer is 10 to the minus 3 nanometers. So this is 0.0024 nanometers. So this is pretty nice. Look, at 90 degrees, cosine theta is zero. So the difference between initial and final wavelengths should be equal to the Compton wavelength with about 0.0024 nanometers. And that's about it pretty close. So this peak is all right. Should've been there. The other peak, why is it there?