PROFESSOR: Last time, we spoke about photons in the context of an interferometer. The Mach-Zehnder interferometer. And we saw the very unusual properties of photons and interference, and how relatively simple interference a effect can be used to produce a very surprising measurement.

Today we're going to backtrack and go from the beginning, and think about photons as physicists did 100 years ago, and how, by thinking about photons, they pretty much came up with quantum mechanics. So we want to trace this back. And the best place to start, probably, is with a photoelectric effect.

The photoelectric effect is an experiment done by Hertz in 1887, in which he irradiated plates. That means shine light, high energy beams of light, on metal plate, and he found that electrons were released. Those were called photo electrons. And therefore, you would get a photoelectric current from those electrons. So this is the effect we want to discuss now, is the photoelectric effect. And it's Hertz, 1887.

So first a description. So polished metal plates irradiated may emit electrons. And these are called photo electrons sometimes. Photo electrons is just an electron that was released due to a photon. And therefore, we get a photoelectric current. OK so so far, so good. But what was special about this experiment?

The first step that was special was that there was a critical frequency. If you would take a sample and you would irradiate it with light, and you would begin with light with very low frequency, nothing would happen. And all of a sudden after a certain frequency, boom. You would get a current. So there is a threshold frequency, nu0, such that only for Nu greater than nu0 there is a current. So no current for lower frequencies.

Now as it turned out, nu0 depends on the metal you're irradiating. And even more, it's a complicated thing to calculate. It depends on the surface of the metal, so that's why Hertz apparently had to polish the metal. And this frequency, if the metal is irregular, may depend on where you shine. So you'd better prepare the metal very nicely. And it may even depend on the crystalline nature of the metal, because it's a many body effect. You see, anticipating the resolution, there is this piece of metal and there are a few free electrons running around. And they run around among the crystalline structure of the metal. And removing them, it's going to take some energy, and that energy depends on the metal and the arrangement and all kinds of things. So this nu0 depends on the metal and the configuration of atoms at the surface.

Third property was kind of interesting. The magnitude of the current was proportional to the intensity of the light. Magnitude current is proportional to the light intensity. And perhaps the last one and fourth, a rather important one, a very crucial property, is that you could observe the energy of the photo electrons, and it seemed to be independent of the light intensity. So energy of the photo electrons is independent of the intensity of light The number of photo electrons would depend on the intensity of light, but not the energy of the photo electrons.

Now there is more to that, but I think it was not quite exactly noticed by Hertz. So Hertz probably didn't notice all these things. But the last one, that maybe we can put in brackets here, is that the energy of the photo electrons E gamma-- oh, no-- E of the electrons increases linearly with the frequency of the light.

So this photoelectric effect was not easy to understand if you thought of light as a wave. And Einstein came up with an answer that he almost said what was going on, but didn't quite use the word. He said that light comes in bundles of energy. And in a beam, you have bundles of energy quanta. Didn't quite say light is a particle. He himself was a little non-committal, I think, about this concept. But Einstein, in 1905, gives the natural explanation and says that light is composed of quanta. He would have to wait until 1920s until the name photons came up, given by a chemist, Lewis. So he called them quanta.

These are later photons, and I will use the name photons from the beginning. With energy, E equal h nu, where nu is the frequency and h was Planck's constant. Planck had already introduced the constant in trying to fit the black body spectrum. The black body spectrum, the intensity of light is a function of frequency in black body radiation, had a particular curve. Planck tried to fit it and he realized he needed one constant and he called it h. That's Planck's constant. And the same constant that Planck introduced, reappeared in Einstein's proposition. This is Planck's constant.

So the picture that Einstein and others had was that you would have kind of a potential here and plot energy over here, and maybe this is some distance. And you have a metal and there is the electrons captured here. And here is zero energy. So they have negative energy, they're captured. And you need some amount of energy, w, which is called the work function, that depends on the type of metal you have. And if you could supply that energy, w, to any one of these electrons that are bound in this metal, they would come out and not be attracted any more and would be able to fly free.

So it is like an escape velocity, you're bound by the gravity of earth. You need something velocity, some energy to shoot you out. Same thing here. So this w, or work function, is defined as the energy needed to release an electron. And that work function is that thing that depends on the metal you have and the structure and how well you've polished the surface. So if this is true, then Einstein, if he was right with this property, there would be the following statement that you could make. The energy of the electron, which is, roughly speaking, one half mv squared, would be equal to the energy that the photon [INAUDIBLE], minus the work function.

So you supply a photon. Some of the energy goes into the work function, but the rest of the energy goes into giving free energy to these electrons. So you have the energy of the photon minus w, which is what you need to just take it out with 0 velocity. And then the rest of the energy of the photon would be transmitted as kinetic energy of the electron. So if this is true, this would be h nu minus omega. And this was considered a prediction, because that statement that the energy of the electron increases linearly with the frequency, was not quite obvious to people. Experiments were not fine enough. Measuring the energy of the emitted particles was not all that easy either.

So this was Einstein's prediction. And the experimental confirmation took 10 years to come. It was verified by Millikan in 1915. So Millikan, in 1915, measures the energy of the photo electrons, verifies Einstein's conjecture, and actually produces, by measuring so carefully the energy of the photo electrons, produces a measurement of h, which is the best to that point. And h is measured to better than 1%, so a very accurate measurement of h.

And perhaps you would say, OK, so this is all wonderful, now everybody believes in photons. But that's quite far from the truth. They didn't believe in photons too much, because Maxwell had been too successful. And Einstein himself knew that once you started believing in particles like photons, you had this subject with this case of loss of determinism and waves that we have sometimes as particles and things he didn't like much. So people were quite reluctant to believe in these things. It's quite amazing. So it took a while still.

So let's do a simple exercise to introduce some numbers here, and show you how to do some very simple computation. So let me do an example. You shine UV light with lambda 290 nanometers on a metal with work function 4.05 EV. What is the energy, E of the photo electrons, and what is their speed?

Now it is a goal of mine, and of the instructors in this course, that a calculation like that, you should be able to do without turning on your iPhone and checking what the h bar is, and getting a few constants, and what is an EV or all these things. Well nowadays, you can just check Wolfram Alpha and they will give you the answer for this, in beautiful, beautiful calculations. Just copy the question like that, pretty much, I think it will answer it for you. But you should be able to do back of the envelope calculations, in which you estimate things quickly. And with one significant digit, you don't even need a calculator to do this.

So let's see how one does this thing. So the first thing to do is to figure out what is the energy of this photon. That's the first problem. So the energy of a photon is h nu. But nu it's not lambda. So nu time lambda is c, so this is hc over lambda, where c is the speed of light. OK, hc lambda, we could do it if we knew h.

I must say, I never remember what h is in normal units. Joule seconds, six point something, I don't quite remember it. So what do I do? I use h bar, which is h over 2 pi. So h is 2 pi h bar c over lambda. And here is where you-- here is the first thing that maybe you want to remember by heart. h bar c is a pretty nice number, it's about 200mev times a fermi, If you want it more precise, it's 197.33, if you want to get five digits, but it's pretty close to 200 mev fermi. And what is a fermi? It's 10 to the minus 15 meters.

OK, so with this number, I claim you can do pretty much all you want to do. So here you have 2pi times 200 mev times 10 to the minus 15 meters divided-- I'll put 197 here-- divided by lambda, which is 290 nanometers, which is 10 to the minus 9 meters. So 10 to the minus 9 and 10 to the minus 15 is 10 to the minus 6 up. And this is a million ev, which is 10 to 6 ev. So all these meters cancel and there's just an ev left. So this is 2 pi times 197 over 290 ev. And you certainly could estimate this like 2 over 3 times 2 pi, which is 6. And that's about four. And if you want to do it more carefully, it comes out to 4.28 ev. And the nice thing is that the answer comes in ev's. And the work functions, everybody gives them in ev's, so it's a convenient thing.

So at this moment, you have this electron energy of the photon being this. So energy of the electron is energy of the photon minus the work function, which is 428 minus 405 ev, and it's 0.23 ev. That's a kinetic energy and that should be a non-relativistic electron because the rest mass of an electron is about half a million ev. It is 511,000 ev. So this is fairly non-relativistic, but how slow is it? Is it moving a centimeter per second? No, it's moving pretty fast.

You can write this as one half mv squared. And then what do you do? You put one half m of the electron c squared v squared over c squared. And this is one half of 511,000 ev times v over c squared. So do the arithmetic, it's 20.46 over that, square root and multiply it by the speed of light. You can do this roughly in your head. And the velocity comes out to 284 kilometers per second, so it's pretty fast.