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8.02 Electricity and Magnetism, Spring 2002
Transcript – Lecture 13

All right, you did well on the exam.

Class average was 62.

I always aim for 65, so I was very happy.

11 students scored 100.

I believe that my exam review was extremely fair.

According to some instructors, perhaps even too close for comfort.

I did a problem with parallel resistors and a battery.

I applied Gauss's Law for cylindrical symmetry.

I spent quite a bit of time discussing where charge occurs and where charge cannot be located on conductors and I hit the idea of capacitors and dielectrics also quite hard.

I prefer not to think about a rigid division between pass and fail, but I'd rather tell you that all of you who scored less than 47, in my book, are sort of in the danger zone.

Now, that doesn't mean that you're going to fail the course, nor does it mean that you will pass the course if you scored 70.

But those people are in the danger zone.

I think you should talk to your instructor, and I would advise those people also to make frequent use of our tutors.

Two exams to go, plus the final.

Today I'm going to uncover a whole new world for you and you will see how 8.02 comes in there in a very natural way.

The Lorentz force F is the charge times the cross product of the velocity of that charge and the B field that the charge experiences.

If I have here a positive charge plus Q and it has a velocity V in this direction, and the magnetic field would be uniform and coming out of the blackboard, there's going to be a force on this charge according to this relationship and the force is then like so.

Perpendicular to V, perpendicular to B.

In this case the charged particle is going to go around in a circle.

The Lorentz force cannot change the speed, cannot change the kinetic energy, because the force is always perpendicular to the velocity, but it can change the direction of the velocity.

And so, what you're going to see is that the charged particle will go around into a perfect circle if the magnetic field is constant throughout.

And the radius of this circle can very easily be calculated using some of our knowledge of 8.02.

The force is QVB because I chose B also perpendicular to V, and so there is no sign, the sign of the angle between them is 1, and this now has to be the centripetal force that we encountered in 8.01, which is MV squared divided by R, M now being the mass of this particle.

And so you'll find now that R equals MV divided by QB.

And this, by the way, I want to remind you, is the momentum of that particle.

If you look at this equation, it's sort of pleasing.

If the charge is high then the Lorentz force is high so the radius is small.

If the magnetic field is high then the Lorentz force is high so the radius is small.

If the mass of the particle is high, there is a lot of inertia and so it is very difficult to make it go around, so to speak, so a very high mass, you expect a very high radius.

And so that looks all intuitively quite pleasing.

Let's do a numerical example.

I take a proton, P stands for proton, and I take a 1 MeV proton.

It's the same I took during my test review.

1 MeV means that the kinetic energy is 1 MeV, is the charge times the potential difference over which this proton was accelerated, in this case, delta V would be 1 million volts.

And this now equals one-half times the mass of that proton times the velocity squared.

In this case, if I have a 1 MeV, so it is a million volts, you will find that this is 1.6 times 10 to the -13 joules.

I gave you there the charge of the proton, you multiplied it by a million, and this is the energy.

And so now you can calculate the velocity because you know the mass of the proton.

I gave you that too, there.

And so you will find exactly what you found during my test review, 1.4 times 10 to the 7th meters per second, which is 5% of the speed of light, comfortably low so we don't have to make any relativistic corrections.

If this proton now enters a magnetic field B, which is 1 tesla, then by using the equation I have up there, you know the mass of the proton, we just calculated the velocity.

You know the charge of the proton and you know the B field.

You will find that R is 0.15 meters, which is 15 centimeters, just a numerical example.

It is more common, or at least often done, to eliminate out of that equation there the velocity and replace it by the potential difference, capital V, over which we accelerate these particles.

And so, what you can do, you can replace this V by using the equation I have there, the one half MV squared, so we have that one-half MV squared equals Q times delta V, but I will write for that just a capital V, and I substitute this V now in here, and so I no longer see the velocity but I now see this potential difference.

In the case of that proton, this V would be a million and you will find then that R is then the square root of 2M times that capital V divided by Q B squared.

And so the two equations are of course the same physics, but it's different representation.

If you put in for V now 10 to the 6th, mass of the proton, charge of the proton, and 1 tesla field, of course you find exactly the same 0.15 meters.

Now this is all nice and dandy, but this works as long as the speed is much smaller than the speed of light.

If that's no longer the case, then we have to apply special relativity and that is not part of this course but I would like to briefly touch upon that today.

I can show you how things go sour because suppose we have a 500 kilo electric volt electron.

So that means that in this equation here, the V is 500000, the Q is the charge of the electron, M is now the mass of the electron, and if I apply that equation I find that V is 4.2 times 10 to the 8th meters per second and that is larger than the speed of light, so that's clearly not possible.

The actual speed, if you make relativistic corrections, is 2.6 times 10 to the 8th meters per second.

And although I don't expect you to be able to make those relativistic corrections, I will make them today and you will see why I have to, and I want to show you that in fact this is not all that difficult even though I will not hold you responsible for these equations.

So what I have here is now kinetic energy, is again QV, that's not changing, but is no longer one-half MV squared but it is gamma minus

1 times MC squared, and gamma is defined there -- it's called the Lorentz Factor, and so if you know now for the electron that capital V is 500000, you can calculate what gamma is from the first equation and then you go to the second equation and you find what the speed is, and you will see then that you never find a speed larger than the speed of light.

And so we now have to make the correction also for the radii and those corrections become again relatively easy.

This now requires a factor gamma and you see that on the upper blackboard there, and this too now has to be replaced by this gamma plus 1 and then everything is OK.

So I don't expect you to know this, but I don't want you to think that all these relativistic corrections come out of the blue, nor do I want you think that it is very difficult.

It really isn't.

The equations are extremely straightforward.

So I want to show you now some of the results that we just discussed.

The 1 MeV proton and the 500 KeV electron, this is on the Web.

You can click on Lecture Supplements and you can make yourself a hard copy.

So here you see the kinetic energy, 1 MeV proton.

Notice the speed that we calculated there is non-relativistic, gamma is very close to 1.

You don't have to make a correction.

And in a 1 tesla field you get a radius of 15 centimeters, which we just calculated.

If you go to a 50 MeV proton, it's sort of in the borderline between relativistic and non-relativistic.

It's still non-relativistic enough, and if it is non-relativistic you can clearly see here that the radius goes with the square root of capital V.

And for 50 MeV, capital V is 50 million, and for 1 MeV, capital V is 1 million.

And since it goes with the square root of V, you expect roughly the radius to be the square root of 50 times larger, which is 7, and indeed, you see that.

So you see, from 15 centimeters the radius goes to about 1 meter.

Um, here is our 500 KeV electron, and notice that I did the calculation correctly.

This is relativistically corrected now.

You get your 2.6 times 10 to the 8th meters per second by applying the formalism that you see there.

I will leave this here throughout this lecture, because I will return to this several times.

I want to show you a cute demonstration.

I have an, er, electron gun here and the electron gun comes like so.

This is the velocity of the electrons.

I put a minus sign there to remind you that they are electrons.

If electrons go in this direction, the current goes in that direction.

And so if now I have a magnetic field which, let's assume the magnetic field is in the blackboard.

This is B.

Then I cross B is the direction of the force.

I is in this direction, B is in the blackboard.

So if I'm not mistaken, I think the force is in this direction and so you will see that it starts to bend in this direction.

If you change the direction of the magnetic field, the magnetic field is coming out of the blackboard, then the electron will go in this direction, and I can show you that here.

It is not too different from the distortion experiment I did when I had the television program there and I had the strong magnet and we distorted the image, but this of course is a little bit more controlled.

So, we're going to see the image there and we want to make it quite dark in the room.

Mmhm.

And turn on the electron gun.

So you see, the electron gun it strikes a fluorescent screen and that's how you can see it, and I have here a bar magnet and if I hold the bar magnet behind it then I can create more or less situations like this.

I can flip over the magnet and then the direction of bending should change, so here I come with the magnet, and you see, curve up the electrons.

I turn the magnet over and I come in again and they curve down.

Very straightforward, very simple.

OK.

There is a fantastic way in physics that we can separate isotopes from one and the same element.

If we, for instance, take uranium, now uranium, when you find it, is for 99.3% percent uranium 238.

That means it has 92 protons, otherwise it wouldn't be uranium, and it has 146 neutrons, 99.3%.

0.7% is uranium 235.

Again, 92 protons, otherwise it wouldn't be uranium, but only 143 neutrons, and that you'll find in nature for 0.7%.

So you go to a chemist and you give a chemist a little bit of uranium and you say would you please separate these two isotopes for me, and he of course would laugh at you and he would say go fly a kite because the chemical properties are exactly the same for the two because uranium is uranium.

Neutral uranium here has 92 electrons and neutral uranium here has 92 electrons, so there's no way that they could separate those.

And I will show you now how they can be separated with what we call a mass spectrometer.

You heat the uranium so that it ionizes.

Let's assume it's ionized once so it loses one electron, so it's positively charged with one unit charge, one of those charges that you see here.

And we now accelerate it over certain potential difference so these uranium atoms, the 235 and the 238 get a certain speed and they come in here with this speed V, so they're positively charged and let's assume that we have a magnetic field that is uniform and that is in this direction, comes out of the blackboard.

So what will happen is that these charged particles which are positively charged now, one unit charge, are going to go around a circle and hit here.

It is a radius.

But if you look here at these equations so you will see that the radius is proportional with the square root of the mass of the particle and the mass of 238 is 1.2% larger than the mass of 235.

And so with 1.2% larger, since we have the square root there, we see here the square root, we accelerate them over the same potential difference, so this one doesn't change.

This is the only thing that changes.

So then you expect an 0.6% change in radius and so the 238 will end up here.

I exaggerate that very highly.

And the 235 will end up here.

The 238 has a larger radius because it has a larger mass, and you see that here.

There's no change in B, there's no change in Q, and there's no change in capital V.

We accelerate them over the same potential difference.

And so if the radius, for instance, were 1 meter of this mass spectrometer then the difference here -- remember this is 2R -- the difference would come out to be about 1.2 centimeters, and so you have a collector here where you collect your 238 nuclei atoms and here you collect your 235 and that is the idea behind a mass spectrometer.

Why did I choose this particular example?

Well, this example changed our world and it made history.

Uranium 235 was needed by the Americans to build an atomic bomb to end the Second World War.

This is- this was done under the famous Manhattan Project.

And Ernest Lawrence of Berkeley built mass spectrometers which were able to separate uranium 235 from 238.

In the beginning, it went very slowly, about 100 micrograms per day.

But a few kilograms was required for an atomic bomb.

They finally managed to get up to 1 gram per day and in combination with other separation techniques such as the gas diffusion techniques which I will not discuss here now they managed to get a few kilograms and they dropped a bomb on Hiroshima on August 6 1945 and three days later a bomb was dropped on Nagasaki.

The Japanese surrendered and it was the end of World War 2.

It's a good thing that there are many peaceful applications nowadays of mass spectrometers, particularly in the medical area.

People sometimes require radiation and they need radiation from a particular radioactive isotopes, but you don't want the other isotopes from the same element and so you separate them then with a mass spectrometer.

It's a whole industry, very important industry.

And I would like to address the issue how you accelerate protons to extremely high speeds, almost approaching the speed of light.

And that is also something for which Ernest Lawrence is credited.

In the early days it was done in a cyclotron, which I will describe to you now.

The cyclotron consists of a chamber which is called a D.

This is one D and here's another D.

These are conducting chambers.

If you look from the side it would look like so.

This is the left chamber and this is the right chamber and all of this is in vacuum and let's assume that we have a magnetic field coming out of the board like so.

Let's revisit our 1 MeV proton.

Suppose I release in this chamber here a 1 MeV proton and I know the speed with which it comes out, because the 1 MeV proton had a speed -- Oh, you still see it there, 1.4 times 10 to the 7 meters per second.

We also know that in a 1 tesla field, let's make this 1 tesla, that the radius is going to be 15 centimeters.

You see it up there.

So what is this proton going to do?

It's going to do this.

But when it gets there, the potential difference is introduced between these two D's, so that this is low pot- high potential and this is a low potential.

And so you're going to get an electric field now in this gap in this direction and so this proton is being accelerated.

And let's suppose that the difference in potential is 20 kilovolts.

Then this proton will gain in electric- in kinetic energy, it will gain kinetic energy, 20 kilo electron volts.

That's the way electron volt is defined.

And so you start off with 1 MeV, so when it has crossed this gap it is now 1.02 MeV.

20 KeV more.

The radius, now, is larger.

If capital V is 2% higher, and I go to this equation, then the radius is 1% higher and so when it comes out here and it makes a circle, the radius now is 1% higher than 15 centimeters.

But when it gets to this part of the D, this potential difference is reversed and so the electric field is again in this direction, in the direction of the proton and so it is accelerated again by 20 kilo electron volts.

Now the radius, of course, is even larger and so very gradually every time that it reaches the gap the potential difference is changed in direction to accelerate the proton and so it gradually spirals out, then, to the largest radius that you have.

So during one full rotation it gains 20 kilo electron volts once, and 20 kilo electron volts twice, so it gains 40 kilo electron volts.

And so the electric fields are doing the work.

They accelerate the particles.

Magnetic fields cannot accelerate.

Magnetic fields can change the direction but they can do no work on the particles.

So the magnetic fields confine the particles.

So let's assume we go 1225 full rotations.

During each rotation the kinetic energy increased by 40 KeV.

And so if you multiply the two then you see now that the kinetic energy of this proton increased by 49 million electron volts, because it went 1225 times all the way around, and so now you have 49 MeV plus the 1 MeV that you started with, so now you have a 50 MeV proton.

You see the second line there?

There we have that 50 MeV proton that I discussed with you earlier.

In a 1 tesla field now the radius is 1 meter, so if this unit had a radius of 1 meter that would be fine.

By that time it would be all the way near the circumference of this unit.

What is remarkable and not intuitive, that the time to go around, as long as we don't have to make relativistic corrections, that the time for a proton to go around is independent of its speed.

Not so intuitive, and you can see this very easily because the time to go around is 2 pi R divided by its speed.

You see, the radius is proportional to V.

And so the time itself is independent of V, because R itself is linearly proportional with the speed and so that cancels and so you'll find now that the time to go around is simply 2 pi times the mass of that particle divided by QB.

And if you correct relativistically, then you have to multiply by gamma, but if you stay non-relativistic, then it's independent of the speed of the protons.

So if we stick to this particular case of our 1 MeV proton that became a 50 MeV proton going around 1225 times, this time to go around once is only 66 nanoseconds, so this is 6.6 times 10 to the -8 seconds.

Give you some feeling of how fast all this is going.

So if you go around 1225 times, that would take only 80 microseconds so in 80 microseconds does all of this occur and that means you have to switch this field twice per full rotation, make sure that the e-field is in this direction, but when the proton comes here the e-field has to be in that direction.

And so the switching frequency which easily be calculated becomes about 30 million times per second, about 30 megahertz.

And all of that takes place in 80 microseconds and you create 1 MeV protons, you turn them into 50 MeV protons.

A mind-boggling concept, but it works.

Quite remarkable.

Now because of the relativistic corrections that you see here with gamma, if you go to very high energies then the time is not constant for a full rotation, so you have to adjust now the frequency with which you switch the potential between these gaps.

So if the time increases then this switching frequency has to go down and we call those instruments synchrotrons, or synchrocyclotrons.

They have names.

So you synchronize now and correct for relativistic effects.

Modern accelerators have constant radii.

They are rings.

And so if you have a ring with constant radius, the only way that you can keep the particles in the ring when they have a low energy and when they have the high energy is by gradually increasing the magnetic field.

So you start off with a weak magnetic field, you go around huge circle, very large radius, and you gradually increase the magnetic field as you keep accelerating them and by making the magnetic field go up just in the right way, maybe all the way up to 2 tesla, you can keep them in that ring.

The first slide that I'd like to show you is the slide of an ancient cyclotron that is actually a synchrocyclotron, was built by Lawrence in Berkeley, and this was capable of accelerating protons to 730 MeV.

You see here a person to give you feeling for the size of this instrument.

Lawrence received the Nobel Prize for Physics in 1939 for his invention of the cyclotron.

The next slide is Fermilab near Chicago.

This is one of these modern accelerators also called sometimes colliders, and this has a diameter of 2.2 kilometers, and this instrument, this here, plans to accelerate protons up to 1000 GeV, G stands for giga, giga is the same as billion.

1000 giga electron volts would be 10 to the 12 electron volts.

The beams of high energy protons are made to collide with other nuclei to uncover the inner workings of nuclear physics.

The higher the energy of the protons, the larger is the impact when the protons collide and the more one expects to learn.

By using ever-increasing energies of the protons, which are nuclear bullets, one explores unknown territory.

In the news, these colliders are often called atom smashers.

That is a flashier name which appeals more to the general public who pays for all this with their tax money.

This research is a multibillion dollar industry.

The words atom smasher are actually a misnomer.

The colliders smash nuclei which are 10000 times smaller than atoms.

And the next slide shows you the tunnel of the largest ring in the world which is in Geneva, at CERN which is a European collaboration.

This tunnel which already exists for many years has a confluence of 17 miles, has a radius of 4.3 kilometers, and in here are these protons being accelerated, of course it's under high vacuum.

And with very modern techniques of superconducting magnets they can even go up now to about 5 tesla.

And in this tunnel right now a whole new experiment is under development which is called the Large Hadron Collider which is considered the Holy Grail for particle physicists and it's hoped that that will go on the air in the year 2007 or so and it will accelerate protons to an unprecedented energy that will give them kinetic energies of 7000 GeV, 7 times 10 to the 12th electron volts.

So I would like to return to my overhead there, so that you can see some of that what we just discussed right there, thank you Tom.

So here we have Fermilab.

You see a radius of 1.1 kilometers.

I showed you a picture from the air and so they went up to 1.5 tesla, so that's the maximum magnetic field strength.

Get very close to the speed of light by the way [laughter] and you see 500 GeV protons.

And here you see the holy grail, the Large Hadron Collider, European collaboration in Geneva at CERN, whereby you have the circumference of 17 miles and the magnetic fields that they hope to achieve going up to 5.5 tesla using modern techniques of superconductors.

So if you want to go around in those tunnels by the way, by the way, you need a motorcycle, to go 17 miles around.

The goal of all this physics, of all these experiments, is to enter new territory, to learn about these mysterious nuclear forces and to see what is inside protons and to see what is inside neutrons.

And with these experiments many nuclear particles were discovered whose existence was completely unknown previously.

Now comes the issue how can you see the results of these collisions of these particles with very high energies.

Well, you can make the tracks of these particles visible.

In fact, today you will see them with your own eyes.

And in the old days this was done with cloud chambers and that's the demonstration I will do today for you.

But nowadays they do them with bubble chambers.

Let's first understand the principle.

If you had a charged particle, whether it is an electron or a proton or an alpha particle -- alpha particle is the nucleus of helium, it's two protons, two neutrons.

If it goes through the air it makes ions and as it goes through the air and it makes ions it slowly loses its kinetic energy and it finally comes to a halt.

If we take a 10 MeV electron 1 atmosphere air it could go 40 meters.

If you take a proton of 10 MeV it would only go 1 meter because the density of ions is higher because it has a higher mass and if you take an alpha particle which has a higher mass than a proton and it has a double charge of a proton, then it would only go 10 centimeters.

It's a very high density track that you would get from an alpha particle.

And so one way you can see these tracks is using cloud chambers, and a cloud chamber works in principle as follows.

You can just have a chamber in air, 1 atmosphere air, which you put liquid alcohol in there, that's the way we will do it, and you cool the bottom.

You see one there, which you will see a little later, and you cool the bottom with solid CO_2 and then you get inside this chamber, you get a temperature gradient and there's a layer there where the alcohol should really condense into little drops because it's that cold, but for reasons that are complicated it doesn't do it quite yet.

We call that undercooled alcohol.

Even rain can be undercooled.

Just below freezing point, still liquid.

When the moment it hits the ground it will immediately become solid, by the way.

That's also undercooled liquid.

Now, here we deal with an undercooled vapor and so when these ions are made by these charged particles, these ions act as seeds for the drops, in this case the alcohol drops, and you can literally with your eyes, visually see these drops being formed.

I'd like to go through one numerical example and I want to go to a 500 KeV electron which you see there.

Um, notice that I have corrected the speed relativistically, otherwise you would get this ridiculous number that we calculated earlier which is larger than the speed of light.

And suppose we have a 1/10 tesla field.

Then the radius would be 2.9 centimeters.

But after a while this electron will lose its energy and then there comes a time that it has only 100 kilo electron volts left.

By that time, the radius in a 1/10 tesla field would now be 1.1 centimeters and so when you look at cloud chambers at the tracks of electrons and you have magnets there, you will see the tracks being curled up which of course is the result of the fact that the radius gets smaller in time and since the magnetic field is constant you can see then large radius here and as the kinetic energy slowly decreases the radius gets smaller and smaller and smaller.

So let's look at a few more slides.

In 1932, Anderson noticed a track in a cloud chamber which had the appearance of an electron.

It had the right mass, it had the right charge, but the curve- the direction of curvature was wrong.

And so he concluded that it was an electron which was positively charged, which is now called a positron.

And these positrons had been predicted on purely theoretical grounds by Dirac, and Anderson receives a Nobel Prize for his discovery in 1936, only four years after he discovered the positron and Dirac had already received his Nobel Prize in 1933 for his theoretical work.

The bubble chamber is an advanced form of the cloud chamber.

In the bubble chamber, liquid hydrogen is used and if now the ions go through, the ions become the seeds now for little gas bubbles.

So you have liquids which really should have been gas but, uh, not quite and so now it forms gas bubbles.

So in a cloud chamber, you're going to see the drops.

In a bubble chamber, you see gas bubbles but the idea is the same, and Glaser who invented these chambers, is also from Berkeley by the way, he got a Nobel Prize for that in 1960.

So let's look at the discovery by Anderson.

Here you see a positron coming from above, and this positron has 63 MeV kinetic energy and Anderson put some half a centimeter of lead in there which was very clever, think about that.

When it comes out, the energy now is less, because in the lead it produces a lot of ions and so it loses a lot of kinetic energy and it comes out with roughly 23 MeV.

And why did he do that?

Because now he knows for sure that this particle came from above, because when it loses energy the radius is smaller.

That's why he was sure that it was curved in the wrong direction.

If he didn't have the lead, you never know whether the electron came this way, in which case the curvature would be perfect.

But now he knows it comes from above and if this had been an electron it would've curved this way.

So this is one of the early discovery, cloud chamber photographed by Anderson.

And the next slide is a bubble chamber and we see here both positron and an electron in a constant magnetic field and it speaks for itself, notice that the curvatures are exactly in opposite directions and you see this spiral structure that I discussed with you as the electrons lose their energy and since this is a bubble chamber, which has an enormous density, 1000 times higher density, say, than air, these electrons don't travel 40 meters in these chambers.

In air they would, but in this case it is substantially less and so you can roll them up nicely.

And you can study them, their momentum and their charge.

Using accelerators and cloud chambers and bubble chambers, a whole new world of nuclear physics emerged.

Wow.

And between 1958 and 68 30 new nuclear particles were discovered.

And MIT has always been on the forefront in this research.

Professor Sam Ting, who is still at MIT, got the Nobel Prize in 1976.

Steven Weinberg, a theoretician who did his work while he was at MIT got his Nobel Prize in 1979.

Jerry Friedman, still at MIT, and Henry Kendall, got the Nobel Prize for their work in 1990.

And Clifford Shull got his Nobel Prize in 1994.

If I summarize the basic idea behind it, it is very relevant to 8.02, you accelerate these particles using electric fields.

That's the only way you can accelerate them.

Magnetic fields can only be used to confine them.

It can not change their kinetic energy but kinetic electr- magnetic fields are crucial, because that allows you as you gradually increase their speed to confine them, either by a ring, which is done nowadays, or in the old days in these chambers of the cyclotrons and the synchrotrons.

And then we have the bubble chambers, in the old days the cloud chambers, whereby you use magnetic fields to get information on the radius of these particles as they are being detected.

And out of all this emerged a whole new way of looking at our world and completely new ideas about what makes the world tick.

This is nothing short of a revolution.

And so now I want to enjoy with you the last 5 minutes of this lecture by looking at a cloud chamber and by looking at some of these tracks.

You're going to see a lot of electrons in there.

The walls of the cloud chamber are radioactive just like you are radioactive.

Your bones are radioactive, your windows are radioactive.

They emit electrons.

No protons, but they certainly emit electrons.

And we have in there a radioactive isotope, a rod, which has thorium in it which produces alpha particles.

And so you're going to see electrons which make beautiful spider web structures.

Please don't clean up yet, we have plenty of time.

To be precise, we have 5 minutes and 18 seconds left.

So these electrons, you will see them going like spiders through this chamber and sometimes they change abrupt direction because they can collide, particularly when they have low energy and then they [break in file] so to speak, and then occasionally we may see an alpha particle coming from our radioactive thorium and that makes a very thick track.

And so let's try this.

We have an expert here which is Marcos who has not only borrowed this instrument, and if you like it we may actually buy it, it's not cheap, we may buy it, but he borrowed it specially for you, for which I'm very grateful, Marcos, and he also did quite a bit of work to get the light just right.

It's not too easy to see those tracks.

So Marcos, you will get a chance to adjust the lights if you want that.

Um.

We're going to make it very dark and let's enjoy then, this wonderful world, invisible world, of nuclear physics.

So here you see this, the rod with thorium.

So Marcos feel free to adjust the light if you feel the need.

I will go into the audience as well and see whether we can identify the electrons.

Oh, there was an alpha particle.

So this is this rod and so the bottom of this chamber is cooled with solid CO_2.

Ah, there was an electron, very nice.

As I said, you know, they almost look like spider webs.

There was an electron here.

Also keep an eye on this rod and occasionally you will see a very dense track which then indicates -- there was one, that's an alpha particle.

There's a beautiful alpha particle.

Just enjoy this.

You know, you're looking at a world which is completely new.

Think about it.

You're looking at the world of nuclear physics.

You're seeing individual electrons and occasionally you see alpha particles.

Here, there's one coming out.

And think about the physics what's going on here, this alcohol which refuses to become drops and then these ions say we force you to become uh -- here's an alpha particle, I don't know what it's doing there.

So these, these, um, these ions force these, um, these, this, this alcohol vapor to become drops.

That's an incredible, complex picture that you're looking at.

It is amazing every time I see this.

It's absolutely fabulous.

And all through these very simple rules, now think about it, we have the Lawrence force, that makes these particles go around, electric fields that you can use them to accelerate them, and then this subtle way that you can actually make them visible, individual particles visible.

It is a new world.

And the goal of my lecture was to make you peek into this world which has revolutionized our whole way of thinking.

Thank you.