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8.02 Electricity and Magnetism, Spring 2002
Transcript – Lecture 21

Yesterday we had 225 motors, and six of those motors went faster than 2000 RPM, which is a reasonable accomplishment.

And the elite is here.

These are the elite, the six highest.

The winner is, um, Jung Eun Lee, I talked to her on the phone last night.

If all goes well, she is here.

Are you here?

Where are you?

There you are.

Why don't you come up so that I can con- congratulate you in person.

I thought about the, the prize for a while, and I decided to give you something that is not particularly high tech, but come up here, give me a European kiss, and another one -- in Europe, we go three.

OK.

Um, the prize that I have for you is a thermometer which goes back to the days of Galileo Galilei -- come here.

Uh, it was designed in the early part of the, um, seventeenth century.

Uh, it doesn't, uh, require any knowledge of 8.02 to explain how it works.

If anything, you need 8.01.

It's not a digital thermometer.

But it's accurate to about 1 degree centigrade, and if you come here, you can tell, you look at these floaters, and the highest floater indicates the temperature.

It's now 72 degrees here.

And I suggest that you brush up on your knowledge of 8.01 so that perhaps next week you can explain to me how it works.

[laughter].

And of course tell your grandchildren about it.

You may want to leave it here.

It's very fragile.

Uh, there is also some package material here, so that you can take it home without breaking it.

So congratulations once more [applause] and of course -- [applause].

Terrific.

And you will join us for dinner on the thirteenth of April with the other five winners.

Thank you very much.

There are two other people who are very special who I want to mention.

And one is a person who is not enrolled in, uh, 8.02, but he did extremely well, and he was very generous.

He was not competing.

His name is Daniel Wendel.

His motor went 4900 RPM.

And then there was Tim Lo.

Is Tim Lo in the audience?

I hope he's going to be there at eleven o'clock.

Tim made a motor -- when I looked at it, I said to myself, it'll never run, but it's so beautiful.

It was so artistic that we introduced a new prize, a second prize, for the most artistic motor, and Tim Lo definitely is the one, by far the best, the most beautiful, the most terrific artistic design.

And so for him I bought a book on modern art -- what else can it be for someone who built such a beautiful motor?

It is here for those of you who want to see it later.

It's very hard to display it on television because it's so delicate.

It's like a birdcage that he built instead of having just -- looks like that it's a birdcage.

It's very nice.

The winning motor I have here, and I'm going to show you the winning motor, and I also want to teach you some, some physics by demonstrating the winning motor to you in a way that you may never have thought of.

So this is the winning motor.

And when we start this motor, the ohmic resistance of the current loop is extremely low.

So the moment that you connect it with your power supply, a very high current will run.

But the moment that the motor starts to rotate, you have a continuous magnetic flux change in these loops, and so now the system will fight itself, and it will immediately kill the current, which is another striking example of Faraday's Law.

I will show you the current of this motor when I block the rotor so that it cannot rotate.

It's about 1.6 amperes.

And you will see the moment that I run the motor that that current plunges by a huge amount.

Striking example of Faraday's Law.

So I now have to first show you this current, so here you see the 1.5 volts, and on the right side you see the current.

There is no current flowing now because the loop is hanging in such a way that the, that it makes no contact with the battery.

And I'm going to try to make it -- there it is.

Do you see the 1.6 amperes on the right?

The current is so high that due to the internal resistance of the power supply, the voltage also plunges.

But you saw the 1.6, right?

Now I'm going to run the motor.

See, the motor is running now, and now look at the current.

Current now, forty milliamperes, thirty milliamperes, fifty milliamperes.

It's forty times lower than when I blocked the rotor.

And so this is one of the reasons why when you have a, a motor, whichever motor it is, it could be just a drill, you try not to block it all of a sudden, because an enormous current will run, and it can actually damage the motors.

So you see here how the current goes down by a factor of forty between running and not running.

All right.

Electric fields can induce electric dipoles in materials, and in case that the, the molecules or the atoms themselves are permanent electric dipoles, an external electric field will make an attempt to align them.

We've discussed that in great detail before when we discussed dielectrics.

And the degree of success depends entirely on how strong the external electric field is and on the temperature.

If the temperature is low, you have very little thermal agitation, then it is easier to align those dipoles.

We have a similar situation with magnetic fields.

If I have an external magnetic field, this can induce in material magnetic dipoles.

And it, uh, induces magnetic dipoles at the atomic scale.

Now in case that the atoms or the molecules themselves have a permanent magnetic dipole moment, then this external field will make an attempt to align these dipoles, and the degree of success depends on the strength of the external field, and again on the temperature.

The lower the temperature, the easier it is to align them.

So the material modifies the external field.

This external field, today I will often call it the vacuum field.

So when you bring material into a vacuum field, the field changes.

The field inside is different from the external field, from the vacuum field.

I first want to remind you of our definition of a magnetic dipole moment.

It's actually very simple how it is defined.

If I have a current -- a loop, could be a rectangle, it doesn't have to be a circle -- and if the current is running in this direction, seen from below clockwise, and if this area is A, then the magnetic dipole moment is simply the current times the area A.

But we define A according to the, the vector A, according to the right-hand corkscrew rule.

If I come from below clockwise, then the vector A is perpendicular to the surface and is then pointing upwards.

And so the magnetic dipole moment, for which we normally write mu, is then also pointing upwards.

And so this is a vector A, which is this normal according to the right-hand corkscrew.

And if I have N of these loops, then the magnetic dipole moment will be N times larger.

Then they will support each other if they're all in the same direction.

I first want to discuss with you diamagnetism.

Diamagnetism.

All materials, when you expose them to an external magnetic field, will to some degree oppose that external field.

And they will generate, on an atomic scale, an EMF which is opposing the external field.

Now you will say, yes, of course, Lenz's Law.

Wrong.

It has nothing to do with Lenz's Law.

It has nothing to do with the free electrons in conductors which produce an eddy current when there is a changing magnetic field.

I'm not talking about a changing magnetic field, I'm talking about a permanent magnetic field.

So when I apply a permanent magnetic field, in all materials, a magnetic dipole moment is induced to oppose that field.

And there is no way that we can understand that with 8.02 It can only be understood with quantum mechanics.

So we'll make no attempts to do that, but we will accept it.

And so the magnetic field inside the material is always a little bit smaller than, than the external field, because the dipoles will oppose the external field.

Now I will talk about paramagnetism.

Paramagnetism.

There are many substances whereby the atoms and the molecules themselves have a magnetic dipole moment.

So the atoms themselves or the molecules, you can think of them as being little magnets.

If you have no external field, no vacuum field, then these dipoles are completely chaotically oriented, and so the net el- magnetic field is 0.

So they are not permanent magnets.

But the moment that you expose them to an external magnetic field, this magnetic field will try to align them.

And the degree of success depends on the strength of that field and on the temperature.

The lower the temperature, the easier it is.

And so if you had a magnetic field, say, like so -- this is your B field, this is your vacuum field -- and you bring in there paramagnetic material, then there is the tendency for the north pole to go a little bit in this direction.

And so these atomic magnets, then, would on average try to get the north pole a little bit in this direction.

Or, if I speak the language of magnetic dipole moments, then the magnetic dipole would try to go a little bit in this direction.

If you remove the external field of a paramagnetic material, immediately there is complete, total chaos, so there is no permanent magnetism left.

If you bring paramagnetic material in a non-uniform magnetic field, it will be pulled towards the strong side of the field.

And it is very easy to, to see how that works.

Suppose I have a magnet here, and let this be the north pole of the magnet and this the south pole.

And so the magnetic field is sort of like so.

Notice right here it's very non-uniform.

And I bring some paramagnetic material in there.

Let's say -- think of it as just one atom there.

It's not to scale, what I'm going to draw.

And here is that one atom, and this one atom now is paramagnetic, has its own magnetic dipole moment.

And this magnetic dipole moment, now, would like to align in this direction to support the field.

The field is trying to push it in that direction.

Let's suppose it is in this direction.

So if we look from above, the current then in this atom or in this molecule is running in this direction.

Seen from above, clockwise.

So that would be ideal alignment of this atom or this molecule in that external field.

This current loop will be attracted -- it wants to go towards the magnet.

Let's look at this point here.

That point, the current is going in the blackboard.

So here is that current I.

And the magnetic field is like so, the external magnetic field is like so.

So in what direction is the Lorentz force?

It's always in the direction I cross B.

And I cross B, I cross B is in this direction.

That's the direction of the Lorentz force.

So right here, there is a force on the loop in this direction.

So therefore right here, there is a force on the loop in this direction, on the current loop.

And so everywhere around this loop, there is a force that is pointing like this, and so there clearly is a net force up.

And so this metal wants to go towards the magnet.

Another way of looking at this is that this current loop is all by itself a little magnet, whereby the south pole is here and the north pole is there, because this is the direction of the magnetic dipole moment.

And the north pole attracts the south pole.

That's another way of looking at it.

That's the reason why magnets attract each other, why north and south pole attract each other, and why north and north poles repel each other.

That's exactly the reason.

It is the current that is flowing, it is the Lorentz force that causes the attraction or the repelling force.

So paramagnetic material is attracted by a magnet.

Essential is that this field is non-uniform.

And diamagnetic material, of course, will be repelled, will be pushed away from the strong field, because in paramagnetic -- in diamagnetic material, this current would be running in the opposite direction, because it opposes the external field whereas paramagnetism supports it.

We have a third form, and the third form of magnetism -- it's actually the most interesting -- is ferromagnetism.

In the case of ferromagnetism, we again have that the atoms have themselves permanent dipole moments.

But now, for very mysterious reasons which can only be understood with quantum mechanics, there are domains which have the dimensions of about 1/10 of a millimeter, maybe 3/10 of a millimeter, whereby the dipoles are hundred percent aligned.

And these dipoles, domains, which are in one direction, are uniformly distributed throughout the ferromagnetic material, and so there may not be any net magnetic field.

If I have here -- if I try to make a sketch of those domains, something like this, then perhaps here all these dipoles would all be hundred percent aligned in this direction, but for instance here, they will all be aligned in this direction.

And the number of atoms involved in such a domain is typically 10 to the 17, maybe up to 10 to the 21 atoms.

So if now I apply an external field, these domains will be forced to go in the direction of the magnetic field, and of course the degree of success depends on the strength of the external field, the strength of the vacuum field, and on the temperature.

The lower the temperature, the better it is, because then there is less thermal agitation, which of course adds a certain rando- randomness to the whole process.

So when I apply an external field, these domains as a whole can flip.

Inside the ferromagnetic material, the magnetic field can be thousands of times stronger than it is in the vacuum field.

And we will see some examples of that today.

If you remove the external field, in the case of paramagnetism, you have again complete chaos of the dipoles.

That's not necessarily the case with ferromagnetism.

Some of those domains may stay aligned in the direction that the external field was forcing them.

If you very carefully remove that external field, undoubtedly some domains will flip back, because of the temperature, there is always thermal agitation.

Some may remain oriented, and therefore the material, once it has been exposed to an external magnetic field, may have become permanently magnetic.

And the only way you can remove that permanent magnetism could be to bang on it with a hammer, and then of course these domains will then get very nervous, and then they will randomize themselves.

Or you can heat them up, and then you can also undo the orientation of the domains.

The domains themselves will remain, but then they average out not to produce any permanent magnetic field.

So for the same reason that paramagnetism is pulled towards the strong field, in case that we have a non-uniform magnetic field, ferromagnetism of course will also be pulled towards the strong field, except in the case of ferromagnetism, the forces with which ferromagnetic material is pulled towards the magnet, way larger than in case of paramagnetic material.

If I take a paperclip -- you can do that at home, you can hang a paperclip on the south pole of your magnet or the north pole of your magnet -- you all have gotten magnets in your motor kit, so you can try that at home.

Take a paperclip, hang it on the magnet.

Doesn't matter on which side you hang it, because ferromagnetic material is always pulled towards the strong field.

If you hang a few of those paperclips on there and you very carefully and slowly remove them -- don't hit them with a hammer yet -- you may actually notice that after you remove them that the paperclips themselves have become magnetic.

You can actually try to hang them on each other, make a little chain.

But drop them on the floor a few times and that magendas- magnetism will go away.

So what you have witnessed then is that some of those domains remained aligned due to your external field.

With paramagnetism, there is no way that you can hang paramagnetic material under most circumstances on a magnet.

There is one exception.

I will show you the exception later today.

And the reason is that the forces involved with paramagnetic material in general are only a few percent of the weight of the material itself.

So if you take a piece of aluminum and you have a magnet, aluminum will not stick to a magnet.

There is a force.

Aluminum will be attracted by the magnet, but the force is way smaller than the weight of the aluminum, so it won't be able to pick it up, unlike ferromagnetic material, which you can pick up with a magnet.

So what I could demonstrate to you, for one thing, I could take a bar magnet and show you that paperclips are hanging on this.

I could also show you that aluminum is not hanging on this.

But you won't find that very exciting.

And therefore I decided on a different demonstration, whereby my goal is to show you that ferromagnetic material is pulled with huge forces towards the strong magnetic field, provided that I have a magnetic field which is non-uniform.

And the way I will do that is with this piece of ferromagnetic material.

And this piece of ferromagnetic material is actually quite heavy.

And you are going to tell the class how heavy it is.

Be very careful.

What do you think?

Wow! Good for you! [laughter].

Do it again! Sounds go-- looks great.

[laughter].

It's fifteen kilograms.

Fifteen kilograms of ferromagnetic material.

It is not a permanent magnet.

There may be a little bit of permanent magnetism left, of course, because once you have exposed it to an external field, yes, there may be some permanent magnetism left.

So now I'm going to hold this -- let's first make sure that nothing happens to Galileo's thermometer.

So we're going to put this here.

See what the temperature is -- oh man, it's going up.

I must be sweating here.

74 degrees, yeah, 74 degrees now.

OK, so here is my magnet, 0:21:30.278 gau producing about 320 gauss.

But what counts is that the magnetic field is non-uniform here and also here.

And so I am going to turn on the magnet -- I believe I have to push a button here.

And the first thing I will do is now power this magnet.

So this is a solenoid.

I put my hand in here, my hand is paramagnetic, it's not being sucked in.

Really it isn't.

I feel nothing.

The force is -- I can't even feel anything.

But I'm not ferromagnetic, thank goodness.

Now this one.

Whssht, fifteen kilograms, just sucked in like that.

And I'm very lucky that when it's overshoots here that it wants to go back, because it always wants to go to the strongest field.

Doesn't matter whether you have it here or there.

The reason why that's lucky, because if that were not the case, this fifteen kilogram bar would go like a bullet coming out of here.

So the one thing you don't want to do when it goes in there, you don't want to break the current, because then it would come out as a bullet.

And I'm not going to do that, believe me.

But I want to show you that -- there it goes.

It's amazing, ferromagnetic material.

Aagh.

OK.

So ferromagnetic material, there's enormous force.

If you have a s- a field that is -- has a strong gradient, that is very non-uniform, is sucked, pulled towards the strong side.

That's why it hangs on magnets.

That's the basic idea.

I have another demonstration.

And another demonstration is to make you sort of see in a non-kosher way magnetic domains.

But I will tell you why it's non-kosher.

I have here an array of eight by eight magnetic needles, compass needles.

And you're going to see them there.

And I will change the situation so that you have better light.

And when I have an external magnetic field and I march over here a little, and I just let it go, and wait, you will see areas whereby these magnetic needles point in the same direction and you will see areas where they point in a different direction.

We'll just give it some chance.

And so that may make you think that this is the way that domains are formed in ferromagnetic material.

Oh, in fact we have now a situation that almost all are aligned in this direction, and there's only a group here that is pointing in this direction.

I can change that, of course, by changing the magnetic field.

Why is this not really a kosher demonstration to convince you that domains exist?

First of all, there is no thermal agitation, whereas in ferromagnetic material there is thermal agitation.

Some may be oriented like this and others like that, where here you only have two preferred directions.

You don't need quantum mechanics for that, simply a matter of minimum energy considerations.

And so they either are pointed like this or they are pointed like that, and so already that shows you that it's very different from ferromagnetism.

But the reason why we show it to you is it still gives you an interesting idea of the fact that you can have various orientations and that they come in groups.

That the groups stick together and are not all in the same direction.

But as I said, it is not really a good way to explain to you why there are domains in ferromagnetic material.

Ah, now you see again, you have some nicely aligned here and others are in very different direction here.

So the basic idea is there.

It's a nice demonstration, but it shows you something that really is not related to ferromagnetism.

The demonstration that is one of my favorites, one of my absolute favorites, is one whereby I can make you listen to the flip-over of these domains.

I have ferromagnetic material inside a coil.

I have here a coil and I'm going to put ferromagnetic material in here.

And I have here a loudspeaker -- an amplifier as well, call this an amplifier.

And this is a loudspeaker.

Let's first assume there is no ferromagnetic material in there.

That's the way I will start the demonstration.

And I approach this with a magnet, and I go very fast.

Whssht, what will happen?

Faraday will say, oh, there's a magnetic flux change, and there will be an EMF in this coil.

That means there will be a current in this coil, induced current.

And it will be amplified and you will hear some sissing noise.

And you will hear that.

If, however, I come in very slowly, you won't hear anything, because d phi/dt is then so low, because the time scale of my motion is so large, that you won't hear any current.

The induced current is insignificantly small.

Because remember the induced current is proportional to the induced EMF, and the induced EMF is proportional to the time change of the magnetic flux.

So I can make that flux change very, very small if I bring it in very slowly.

Now I will put in the ferromagnetic material, and I will approach it again very slowly.

And now, there comes a time that some of those domains go *cluk*, *cluk*.

But when the domains flip over, there is a magnetic flux change inside the material, and so the magnetic flux change means d phi/dt, and it's on an extremely short time scale.

And so now you get an EMF, you get a current going through the wire, and you hear a cracking noise over the loudspeaker.

And for every group of domains that flip, you can hear that.

And that's an amazing thing when you think about it, that some 10 to the 20 atoms go clunk and that you can hear that.

And so this is what we're going to do here, and I will do it then in, in several steps, so that you first can hear the noise if I don't have ferromagnetic material, and then -- so here is the, here's the coil.

This is a very small coil.

And here is a magnet.

And I'll come very fast towards the coil.

What you heard now is Faraday's Law.

You simply have a magnetic flux change in the coil -- oh, I shouldn't touch it.

Now I come in very slowly, and go away very slowly.

You hear nothing.

d phi/dt is just too low.

Now I put in the ferromagnetic material.

Put it inside the coil.

And now I approach it again, very slowly.

There they go.

You hear them?

Those are, those are domains that go.

I'll come in with the other side.

There it goes, the domains.

Isn't that amazing?

You hear atoms switch, groups of atoms.

I'll turn it over again.

Now they flip back.

They don't like it that that's their problem.

This is called the Barkhausen effect.

I find it truly amazing that you hear groups of atoms, 10 to the 20 atoms at the time, they flip over, and when they do, there is a magnetic flux change inside the ferromagnetic material, is sensed by the coil, and you hear a current.

And if I do it fast, uh, these, these, these, these domains go haywire.

They go nuts now.

Imagine that you were a domain and I would treat you that way.

You'd go *cluk*, *cluk*, *cluk*, *cluk*, *cluk*.

But the fact that you can hear it is absolutely amazing, isn't it.

So that's actually a nice way of demonstrating that these domains exist.

If you did that with faramagnetic- paramagnetic material, you wouldn't hear that.

So in all cases, whether we have diamagnetic material or paramagnetic material or ferromagnetic material, uh, the magnetic field inside is different from what the field would be without the material.

And what the field would be without the material we've called external field.

I've called it vacuum field.

And in many cases, but not all -- next lecture I will discuss the issues of not all -- in many cases but not all cases, is the field inside the material proportional to the vacuum field.

And if that is the case, then you can write down that the field inside is linearly proportional -- so this is the field inside the material, regardless of whether it's diamagnetic or paramagnetic or ferromagnetic, is proportional to the vacuum field.

I will write down vacuum for this.

And this proportionality constant I call kappa of M.

I -- our book calls it K of M.

And it's called the relative permeability.

And so now we can look at these values for the relative permeability and we can immediately understand now the difference between diamagnetic material, paramagnetic material, and ferromagnetic material.

Since in the case of diamagnetic material and paramagnetic material, the B field inside is only slightly different from the vacuum field, it is common to express kappa of M in terms of 1 + something which we call the magnetic susceptibility, which is chi of M.

Because if it is very close to one, then it is easier to simply list chi of M.

And let's look at diamagnetic material.

Notice that these values for chi of M are all negative -- of course, they have to be negative, otherwise it wouldn't be diamagnetic.

It means that the field inside is slightly, a hair smaller than the vacuum field, because these induced dipoles oppose the external field, remember.

It has nothing to do with Lenz's Law, but they oppose it nevertheless.

And so you express it in terms of the, um, magnetic susceptibility, and so you have to take 1 - 1.7 times 10 to the -4 to get kappa of M, which is very close to one.

If now you go to paramagnetic materials, the minus signs become plus.

Again, the numbers are small.

But the fact that it is plus means that inside paramagnetic material, the magnetic field is a little, a hair larger than the vacuum field.

But now if you go to ferromagnetic material, it is really absurd to ever list the value for chi of M, because chi of M is so large that you can forget about the one, and so chi of M is about the same as kappa of M.

And so you deal there with numbers that are 100, 1000, 10000, and even larger than 10000.

That means that if kappa of M is 10000, you would have a field inside ferromagnetic material that is 10000 times larger than your vacuum field.

Next lecture I will tell you that there is a limit to as far as you can go, but for now we will, we will leave it with this.

So paramagnetic and ferromagnetic properties depend on the temperature.

Diamagnetic properties do not depend on the temperature.

So at very low temperatures, there is very little thermal agitation, and so you can then easier align these dipoles, and so the values for kappa of M will then be different.

For ferromagnetic material, if you cool it, you expect the kappa of M going up, so you got a stronger field inside.

So it's temperature-dependent.

If you make the material very hot, then it can lose completely its ferromagnetic properties.

What happens at a certain temperature, that these dosmain- domains fall apart, so the domains themselves no longer exist.

They annihilate.

And that happens at a very precise temperature.

It's very strange.

That's also something that is very difficult to understand, and you need quantum mechanics for that too.

But at a certain temperature, which we call the Curie temperature, which for iron is 1043 degrees Kelvin, which is 770 degrees centigrade, all of a sudden the domains disappear and the material becomes paramagnetic.

In other words, if ferromagnetic material would be hanging on a magnet and you would heat it up above the Curie point, it would fall off.

It would become paramagnetic, but paramagnetic material in general doesn't hang on a magnet, because the forces involved are quite small.

And the change is very abrupt, and I am going to show that to you with a demonstration.

I have a ferromagnetic nut.

It's right there.

You will see it very shortly.

And this nut, or washer, hanging on a steel cable, and there is here a magnet.

I don't know whether this is north or south.

It doesn't matter.

And here we have a thermal shield.

And so this washer is against the thermal shield, because it's being attracted.

It wants to go towards the strong magnetic field.

It's ferromagnetic.

So it will be sitting here.

And now I'm going to heat this up above the Curie point, 770 degrees centigrade, and you will see it fall off.

And when it cools again, it goes back on again.

So I can make you see ferromagnetic properties disappear.

And let me make sure I have the proper settings.

I see nothing.

I see nothing.

But there it is.

So here is this nut, and here is this shield, and the magnet is behind it, you can't see it, but it's right there.

And so it goes against it, right, it goes just towards the magnetic poles.

It goes into the strong magnetic field.

The magnetic field is non-uniform outside a magnet, and it goes towards it.

And so now I'm going to heat it.

It will take a while, because, um, 770 degrees centigrade is not so easy to achieve.

The three most common ferromagnetic materials are cobalt, nickel, and iron.

Nickel has a Curie point of only 358 degrees centigrade, so if this were nickel -- ooh.

If this were nickel -- uh-uh.

[laughter].

Oh, you like that, huh.

I think I need strong hands.

A strong hand is coming.

OK.

I think I fixed it.

I'm a big boy, I did it myself today.

I lost my pen, but that's a detail.

OK, let's try again.

So I'm going to heat it up, and I was mentioning that, um, nickel has a Curie point of 358 degrees centigrade.

So that's quite low.

This is 770.

Cobalt is 1400 degrees Kelvin Curie point.

Gadolinium is a very special material.

Gadolinium is ferromagnetic in the winter, when the temperature is below 16 degrees centigrade, but it is paramagnetic in the summer, when the temperature is above 16 degrees centigrade.

It's beginning to be red-hot now.

770 degrees centigrade, you expect some visible light in the form of red light -- there it goes.

And I will keep it heating, I will keep the torch on it, so that you can see that indeed it's no longer attracted by the magnet.

And the moment that I stop heating it, it will very quickly cool.

It will become ferromagnetic again, and it will go back.

Just watch it.

There it goes.

So now it's again ferromagnetic.

So the transition is extremely sharp.

All right.

Uh, OK.

So paramagnetic materials, as I mentioned several times, in general cannot hang on a magnet.

The attractive force is -- there's not enough.

To hang on a magnet, the force has to be larger than its own weight.

And diamagn- diamagnetic materials is of course completely out because diamagnetic materials are always pushed towards the weak part of the field.

It's only paramagnetic materials and ferromagnetic materials that experience a force towards the strong part of the field if the field itself is non-uniform.

Now there is one very interesting exception.

And I want to draw your attention to this, um, transparency here.

Look here at oxygen at one atmosphere.

Oxygen at one atmosphere and 300 degrees Kelvin has a value for chi of M which is 2 times 10 to the -6.

But now look at liquid oxygen at 90 degrees Kelvin.

That value is 1800 times larger than this value.

Why is that so much higher?

Well, liquid, in general, is about thousand times denser than gas at one atmosphere.

So you have thousand times more dipoles per cubic meter that in principle can align.

And so clearly you expect an immediate one-to-one correspondence between the density, how many dipoles you have per cubic meter, and the value for kappa M -- for chi of M.

And so you see indeed that this value is substantially larger.

The reason why it is more than a factor of thousand higher is that the temperature is also lower.

You go from 300 degrees to 90 degrees, and that gives you another factor of two, because when the temperature is lower, there is less thermal agitation, and so the external field can align the dipoles more easily.

And so that's why you end up with a factor of 1800.

Even though this value for chi of M is extraordinarily high for a paramagnetic material, notice that the field inside would only be 0.35% higher than the vacuum field, because if chi of M is 3.5 times 10 to the -3, that means that the field inside is only 0.35% higher than the vacuum field.

But that is enough for liquid oxygen to be attracted by a very strong magnet, provided that it also has a very non-uniform field outside the magnet.

And so the force with which liquid oxygen is pulled towards a magnet can be made larger than the weight of the liquid oxygen.

And so I can make you see today that I can have liquid oxygen hanging from a magnet.

And that's what we are going to do here.

Make sure I have the right setting.

Ah, this is it.

Now we're going to have some changes in the lights.

So there you see the two magnetic poles.

It's a electromagnet.

And so we can turn the magnetic field on at will.

So here are the poles of the magnet.

And the first thing I will do is very boring.

I will throw some, uh, liquid nitrogen between the poles.

Now I don't have the value for liquid nitrogen there, but nitrogen is diamagnetic, so it's not even an issue.

Diamagnetic material is pushed away from the strong field.

So even though the value for chi of M will be very different for liquid nitrogen than it is for gaseous nitrogen, it doesn't matter.

So certainly it will be pushed out.

So that's the first thing I want to do, just to bore you a little bit.

Because I have to keep you on the edge of your seat before you're going to see this oxygen, which will be hanging in there.

So let's first power this magnet -- I hope I did that -- yes, I think I did.

And here comes the liquid nitrogen.

Boring like hell, just falls through.

Now comes the oxygen.

Liquid oxygen.

It's hanging in there.

I challenge you, you've never in your life seen liquid hanging on a magnet.

You can tell your parents about it -- and of course your grandchildren.

It's hanging there.

I'll put some more in -- make sure I have the right stuff, yeah.

Put some more in.

There is liquid oxygen.

When I break the current, it's no longer a magnet, it will fall of course.

Don't worry, you'll get more.

Who has ever in his life seen a liquid hang on a magnet?

It's paramagnetic, it's not ferromagnetic, but because the density is so high and because it's so cold, the value for chi of M is high enough that the force on it is larger than its own weight.

If you do this with aluminum, not a chance in the world.

Aluminum will not hang in there, even though aluminum, as you can see there, is paramagnetic.

But the value 2 times 10 to the -5 is way too small, and it will not stick to a magnet.

OK.

You have something to think about.

I will see you Friday.