MIT OpenCourseWare
http://ocw.mit.edu

3.091SC Introduction to Solid State Chemistry, Fall 2010
Transcript – Session 17

PROFESSOR: Let's get right into it. So last day, we started looking at Roentgen again and the generation of x-rays, which we saw occurred when we operate the gas discharge tube at high voltage and low pressure and this is the image that we saw of his wife's hand. Birth of medical radiography. And we started looking at the origin of x-rays and we started looking at the energy level diagram of the target anode in the gas discharge tube and this is the energy level diagram of the target. So the ballistic electron-- I'm calling it incident-- this is the electron that's making its journey across the x-ray generating tube. It left the cathode and it's moving across and crashing into the anode. So this is the target or the anode. So let's label it as such. So we're looking at one of these mixed metaphors, where we've got both a Cartesian image here of the electron and we've got an energy image. So this is the target or it's the anode and it's charged positively and so the electrons are crashing into it.

And we reason that what would happen is, if the electrons, the ballistic electrons, had high enough energy, they could actually dislodge 1s electrons and when they do so, they make the conditions for a cascade. So you can see electrons falling from n equals 2 to n equals 1 and when they do so, they emit radiation. They emit photons and these photons are called K alpha. K because the final shell number was n equals 1. And remember, the spectroscopists prefer to use letters. So when the electron ends at n equals 1, that's n final, we call it a K photon. And furthermore, the subscript alpha means that the delta, the n initial to n final is only one. So when you go from 2 to 1, you get the K alpha. And less likely but still possible is the transition from 3 down to 1. So it's still called a K photon because the electron that generated the photon ended in the K shell, but it traveled from a delta n of 2, went from 3 to 1 so that's a K beta.

Over here, obviously if we have enough energy to kick out K shell electrons, we have enough energy to kick out L shell electrons. And so if we lose an L shell electron and we have a cascade, then anything that ends in n equals 2 will be called an L photon. If it comes from 3 to 2, that's a delta of 1. That's the L alpha. It it falls 4 to 2, that's a delta of 2. That's the L beta. And so you can see you get a set of lines. And that set of lines looks like this. We can plot a spectrum of this entire set of lines, which will be characteristic of the identity of the target.

And I think I showed you last day that it's going to look like this, where we will plot intensity and the intensity on a spectrum is related to the frequency of occurrence and on the abscissa, we're going to have some kind of energy coordinate. We can put lambda increasing from left to right, which means energy increases from right to left.

And we saw that we have this family of lines where we have a discrete line at the energy of K alpha and a second line at the energy associated with K beta and K beta has a higher energy, therefore, a lower wavelength, and the relative heights related to the relative frequency, again, not to scale, but still the general relationship is correct. The likelihood of falling from 2 to 1 is higher than falling from 3 to 1 and so you'd expect to have the intensity of the K alpha line greater than the intensity of the K beta line and the L lines have to be of lower energy because transitions 3 to 2 are less energy than 2 to 1 so we expect those lines to be out here and again, a relative frequency where the L alpha has a slightly lower energy and L beta has a slightly lower frequency of a current.

So that's the spectrum and this we call characteristic. Characteristic of what? Of the identity of the anode or the target. This is generating the x-rays. So if I want x-rays of this value of wavelength, I choose the target appropriately. That's why we have the relationship here. And then the other thing is that-- it's obvious, but I just want to make sure that we put it up here-- it's quantized because we're looking at the photons coming at discrete values of energy. So that's what we speculated on. Are there any data? The answer is yes and the data come from a young man by the name of Henry Moseley. He was doing his PhD up in Manchester. He was is working for Rutherford. Rutherford was his PhD thesis supervisor and 1913, 1914, he was making systematic measurements. He was conducting a systematic study of the characteristic spectra of no fewer than 38 elements of the Periodic Table.

And what did we learn from his measurements? Learned from his measurements that there's was a pattern here and here's what the pattern is that Moseley found. He found that if he took the value of-- I'm going to just take one line. If he took all of the K alpha lines from 1K alpha per element and he plotted the value of the wave number of a particular line, he found that the value of the wave number of a particular line scaled with the identity of the element by the square of the proton number. So, for example, we would have, say here we started with aluminum. So aluminum proton numbers 13 so 13 squared. And he went all the way up to gold. Didn't do all of them but he did, as I say, 38 from one to the other. And these are discrete values. You have different elements here and gold is up here and he found that he could take the set of data for, say, all the K alphas and they lie on a line-- new bar-- as if proportional to the square of the proton number and he did the same with other lines-- say, L alpha and so on-- found that they lie on a line.

So what does all of this mean? Well, let's take a look. Here's the image of the paper. High-frequency spectra elements. Henry Moseley, Master's degree, so he's working on his PhD, and the data were taken as follows in photographic plates. And so by trigonometry, you can figure out what the wavelength would be of the line that would go to this degree of distortion, et cetera, et cetera.

It's a beautiful set of lines. Look at how these date are posed. So there's calcium. Scandium is frightfully expensive so you don't see it here. Then there's titanium, vanadium, chromium, manganese, and as you change the element, the wave number, the wavelength, the energy of all of these lines changes systematically in accordance with the square of the proton number, and we got over here to copper. Next one is zinc. Zinc melts at 420 degrees Celsius, which is relatively low melting. And under the bombardment of electrons-- the bombardment of zinc would cause it to melt and so rather than work with zinc, he instead worked with brass because brass is an alloy of copper and zinc-- and look carefully. You can see that brass has four lines, two lines identical to the lines of copper and these two new lines are the lines associated with zinc. And I mentioned last day that you could actually deconvolve the complex spectra and identify the constituent elements. So this was really fantastic, really fantastic.

Si what did we learn from all of this? What did we learn by these data? well, first of all, corrected Mendeleyev What do I mean by that? Not here to say bad things about Mendeleyev, but Mendeleyev had told us that periodicity is a function of the atomic mass. That's what Mendeleyev said. Periodicity is a function of atomic mass. And now Moseley says no. Moseley says that periodicity is a function of proton number.

And you can see here-- I wanted to show you the-- this is an image taken from his paper. He worked for Rutherford. These people were brilliant experimentalists and so here he's got-- the cathode is up here at the top. You see cathode of x-ray tube and the feed through and so on, so the anode is down here and it's connected and so on, and rather than take the x-ray tube apart in order to change the target, he went to the toy store and he bought-- this is the train from the toy store and he's got different elements seated next to each other on the flat car of the train and he's got feedthroughs with silk fishing line so that after he's done the experiment with one element, he can pull the train car over and change the anode without having to take the apparatus apart. These guys were very, very good experimentalists.

So here's from his paper. The author intends first to make a general survey of the principal types of high-frequency radiation and then to examine the spectra of a few elements in greater detail with greater accuracy. The results already obtained show that such data have an important bearing on the question of the internal structure of the atom and strongly support the views of Rutherford and Bohr. It's 1913. Remember, that's when Bohr paper came out. All these people were working in the lab at the same time, supporting each other. You see, this doesn't make any sense with a Plum Pudding Model, does it? See, he continues: "We have here a proof that there isn't the atom of fundamental quantity, which increases by regular steps as we pass from one element to the next. This quantity can only be the charge on the central positive nucleus on the existence of which we already have definite proof."

See, not only-- remember, the Plum Pudding Model has this big blob of positive charge nests. There are no protons. In the nuclear model, we have a nucleus that has positive charge and he's saying, I know there's positive charge, and it increases as you go from one element to the next. We are therefore led by experiment to view that N-- we use the letter Z today. He's using capital N. N is the same as the number of the place occupied by the element in the periodic system. This atomic number-- for the first time, the term atomic number is used.

That's why I was being coy here and I kept saying proton number, because that's the way they knew it. Now he's say, this is the social security number of the element. Proton number is then for hydrogen 1, helium 2, lithium 3, calcium 20, zinc 30, et cetera. We can confidently predict-- look at-- this is the masters student and he's going on a limb. He says: "We can confidently predict that in the few cases in which the order of the atomic weights A clashes with the chemical order of the periodic system, the chemical properties are governed by N, while A itself is probably a complicated function of N." He's right.

You look at the Periodic Table. You say, yeah, yeah, they just go in descending mass or ascending proton number. Look carefully. Potassium has a lower mass than argon. And nobody's to-- well, if you were Mendeleyev, you'd say, go back and measure it again. Well, they have measured it. These are the accurate values and no one's going to put potassium underneath neon, but it comes next in the order of ascending atomic mass. Cobalt and nickel-- nickel actually weighs less than cobalt. But they're transition elements so who cares if you get those two mixed up? You find them in stainless steel. It doesn't matter. This is a good one. Iodine is lower mass than tellurium. Iodine is a halogen. It belongs under fluorine, chlorine and bromine. You're not going to put it under oxygen, sulfur, selenium. But look, there's the data. And then last one that Moseley couldn't have known about is transuranic synthetic element, but that's just the fourth case in the periodic table. So that gets you the last wedge in Trivial Pursuit. What are the four pairs of elements that are out of sequence? OK.

So now we can say that proton number is the atomic number. It's the identity. So that comes out of Moseley, comes out of his work. The second thing that he did as a result of his study of 38 elements is he figured out what to do with the lanthanides. Remember our friends, the lanthanides. Place the lanthanides correctly in the Periodic Table.

Many of the lanthanides have a valence 3 so people were struggling. They were putting them underneath aluminum. They didn't know what to do with them. He placed the lanthanides correctly in the Periodic Table. And it's not as though these were brand new. Lanthanum itself had been first isolated in 1839, and all through the 1800s, they were picking them up and finally, lutetium was the last one discovered, categorized in 1907.

But people didn't know what to do with them and remember, they were obsessed with atomic mass measurements. So I'm going to give you this. I'll give you this piece of information. There's the atomic mass of lanthanum, and the atomic mass of lutetium is 174.97. So what? I don't know what to do with that information. That doesn't help me at all.

But now comes Moseley and he says, we're not talking about atomic mass. We're talking about atomic number. So now I tell you this atomic number is 57. So where do you put it? Duh, you put it right next to barium. There's no debate. And furthermore, this one is 71-- atomic number. Well, if this is 71 and this is 57, I can tell you with impunity-- how many lanthanides are there? There's 14 of them from here to there. OK. 14 elements, which makes sense because in s we've got one orbital, in p we've got three orbitals, and d we've got 5 orbitals and these are f and there's 7 orbitals. 7 times 2 is 14. Everything makes sense. And the last thing that's a corollary to the item two-- we were able to give uranium its proper atomic number is 92. So now I ask you, how many elements are there up to uranium starting with hydrogen? 92. All of this comes as the result of Moseley's experiments.

But it's not over yet because he worked for Rutherford, and Rutherford pushed his people really hard. He wasn't abusive, but he brought out the best in them. So who else was in the building? Bohr, and what were they doing? They were doing theory and so he said, well, that's nice, but he says, I want those things fit to an equation. So Moseley said, all right. I'm going to use-- there's already an equation in the building for a new bar. It's the Rydberg equation. So I'm going to use a Rydberg-like equation. So this is what he does. This is Moseley's fit. He goes the wave number of whatever the line is-- whether it's K alpha, L alpha, what have you-- is going to go as the product of the Rydberg constant-- 1/NF squared minus 1/NI squared. So far that's just the Rydberg equation.

But now comes Moseley's contribution. We're going to put z squared, but one more piece. Notice the way I've drawn those lines. They don't go through the origin, do they? There's an offset. So he said, let's allow for the offset-- z minus sigma quantity square. And this is known as Moseley's Law. And you've got values for sigma. sigma for K alpha equals 1 and for L alpha equals 7.4. So now I can-- with impunity, you give me the wavelength. I can get the wave number-- it's 1 over the wavelength and I can plug into this equation and identify the element or turn it around if I want to get wavelength radiation of, say, 1.25 angstroms, I can plug into this equation and come up with the z, which will tell me what the target element choice should be. So let's go and plug this in because we're only going to look at these two.

So we can say that the wave number for K alpha-- it's always going to be 1/2 squared minus 1/1 squared, which is always going to come up 3/4. So it's 3/4 times Rydberg z minus 1 squared. So this is for the 2:1 or, if you like, L to K transition and then the other one of interest here is nu bar of L alpha. nu bar of L alpha's going to be 1/3 squared minus 1/2 squared, which becomes 536 times the Rydberg constant z minus 7.4 squared and this is for the transition 3:2 or KLM, M to L. OK. So there it is.

And now, what's the significance of all of this? I try to give a physical significance of this sigma, which is known as the screening factor. We're going to call sigma here the screening factor. You'll see why in a second. Why are we calling it the screening factor? So let's consider what's happening in the case of the K alpha lines. Let's look at K alpha generation. So not to scale. Let's draw-- here's the nucleus with all of its z positive charges and then I'm going to draw the K shell, and its got two electrons in it, and I'm going to show there's a hole here. Because without this hole, there's no reason for the cascade. And then I'm going to draw the L shell and it's got-- what? There's 2 from the s, 2s, and then 6 from the 2p. At most. I know this is a terrible model. It violates all kinds of things, but it's as complex as it needs to be for the explanation I'm about to give and I don't want to load you down with a whole bunch of extraneous information.

So consider the electrons in the L shell. They see the electron vacancy in the K shell and they're going to fall down. What's the Coulombic pull of the nucleus on the L shell electrons? Can you see that it's not z plus, but at z plus screened by 1 minus. So the nuclear charge is mediated-- in other words, it's reduced by 1 thanks to the presence of the one negative charge here. So these electrons in L shell feel z less 1 and hence, we get z minus 1 as screening factor. It's plausible. It's at least physically consistent.

Now let's look at the next one. That's the transition from M to L. OK. So we get to M. We've got 18 electrons, up to maximum of 18, and if they're going to fall down to n equals 2, there needs to be at least one vacancy here. So now let's use the same logic. So an electron in the m shell sees the positive charge of the nucleus mediated by the electrons between the shell n equals 3 and the nucleus.

Now, I don't know how many electrons there are. What's the extreme case here? Two, four, six, seven, maybe eight, nine. Because this would still give me the conditions to generate the transition 3 to 2. I need a vacancy in two. I don't need a vacancy in one. So this is the maximum. so that would be two, four, six, eight, nine. So it could be z minus nine, but that would mean that all of these electrons are on the same side and I don't have any vacancies lower. I only have one vacancy here. That's an extreme. It's not observed.

And the other extreme is, we blow away all the electrons. So somewhere in between 9 and 0, it turns out it's 7.4. I can't predict that it's 7.4, but 7.4 makes sense. If the number were greater than 9, I would be distressed. So it makes sense, rationalizes. OK. And by the way, if you use this formula, Moseley's Law-- let's bring that back down. Remember, I told you I can still wake up in the middle of the night and quote you the wavelength of copper K alpha radiation of five significant figures. I had it drilled into me in my junior year. It's 1.5418 angstroms. That's the lambda. So you can use this formula for new bar and you know that new bar is equal to 1 over lambda. So I can use Moseley's Law.

But true value, lambda-- I love this one. Watch. I'm going to do a triple subscript. Lambda of copper K alpha. Isn't that cool? Lambda of copper K alpha is equal to 1.5418 angstroms. And if you use Moseley's law, you get 1.546 and the delta here is 1/3 of 1%.

This man was a positive genius. He was heading pell-mell for the Nobel Prize, but he never got it. Why not? World War I broke out in 1914 and Moseley was passionately concerned about World War I. He wanted to fight. He wanted to fight for the Allied cause and he enlisted in the Army. Rutherford was furious. Rutherford called the Minister of War, which is analogous to the Secretary of Defense and said, give him a desk job. Put him up in Oxford at a military laboratory. And Moseley said, no, I refuse. I'm going to fight. And so he was sent to Gallipoli. Gallipoli, as you may know, was one of the bloodiest sites of World War I. A quarter of a million Allied troops and 1/3 sort of a million Turkish troops were killed at Gallipoli. Almost 2/3 of a million people died for that little piece of land. And on August 10th, 1915, at the age of 27, Henry Moseley was killed in the battle of Suvla Bay, and they don't give Nobel Prizes posthumously, and so that was the way it ended.

There's a shot of Henry Moseley with one of his books. The tributes poured in from all over the world. The physics community was devastated because they knew all of this stuff. This is the one that really, I think, says it best. This was written by Robert Milliken, an American. He's the one that gave us the elementary charge of the electron, from the University of Chicago at the time. This is what Milliken wrote-- wrote this to Rutherford to read. "In a research which is destined to rank as one of the dozen most brilliant in conception, skillful in execution, and illuminating in results, a young man 26 years old threw open the windows through which we can glimpse the subatomic world with a definiteness and a certainty never dreamed before. Had the European War no other result than the snuffing out of this young life, that alone would make it one of the most hideous and most irreparable crimes in history." That's when American scientists knew to write. It's beautiful writing. What a tribute. OK.

So let's move on. Now that we've got Moseley's Law, we've straightened out the Periodic Table. So we keep moving. And I say, well, I gave you the drawing of the spectrum. Remember the spectrum? The spectrum was here. You see it? I'll put it up real quick again. This was the spectrum. OK. This is intensity and this is wavelength and this is K alpha and this is K beta and this is L alpha and this is L beta. These are the data coming from the x-ray tube. This happens to be a molybdenum target.

Well, it doesn't quite look like what I've drawn, does it? It looks a little bit like it, but not quite. This is definitely there. You can see some of these lines so I'm going to call this spectrum A and it looks like spectrum A has been added on top of something else. I'm going to call the something else spectrum B and the spectrum B looks like this. And in New England-- this curve has a shape because it's New England. This is called whale-shaped. I don't know what they call it in the rest of the country, but it even looks like a whale. So you can go on a whale watch. So it starts-- it's a sharp front, goes straight up, hits the maximum and then-- are you ready for this? It tails off, all right? Whales have tails, yes. So what's the difference here? Well, the spectrum A, we already observed is quantized, whereas this one isn't. This one's continuous. It has continuous values up to this minimum value or, if you like, maximum value of energy, minimum value of wavelengths. So we got that. It's not quantized.

And the other thing that's interesting is-- spectrum A, we said, is a function of the identity of the target. z of the target, whereas this one, it's a function of the plate voltage. So you can see in the diagram I've shown you, as the plate voltage changes, we get a series of enveloping curves. So this is V1 and this is V2-- greater than V1. So this whale-shaped thing is somehow related to plate voltage.

And then beyond a certain critical value, can you see when you're down here at 15 or 20,000 volts, all you got is the whale-shaped curve? But somewhere between 20 and 25,000 volts, you hit a threshold and now you switch on the characteristic lines. So with low voltage, you don't get the characteristic lines. You only get the whale-shaped curve. And then beyond a certain critical value of V, it's as though all of a sudden these lines appear. Low voltage, no lines. High voltage, you get the characteristic lines.

And what can we do here? Well, we can compute K alpha, L alpha by Moseley's Law. The continuous spectrum can't do anything with that, with one exception-- here. So let's look inside and figure out what's going on. We have a proposal here of what's going on inside that target atom. So I'm going to make-- this could be the molybdenum target up there. So these are molybdenum atoms. And just as in Moseley's figure-- so this is body centered cubic-- I can look that up on the Periodic Table. I know this is BCC crystal structure, molybdenum atom sitting here. This is the anode. It's charged positive and way up top, I get the cathode. So the cathode is shooting off ballistic electrons and they go zooming across the gap and crash into anode, but up until now, we've just said the anode is some material. Now we're going to take one more peel off the onion and say that these are discrete atoms. It's not continuous molybdenum. It's molybdenum atoms.

And what do we know the molybdenum atom looks like? It's got a dense nucleus where all the positive charge resides and then there's this almost vacuum-like zone with the negative charge. So when the electron comes in, this electron sees the negative charge around the molybdenum atom. What happens? It's deflected. Maybe it comes in on a closer angle and it's scattered through a higher angle. Maybe it comes in almost in between and it hardly moves at all.

Now can you see that when you have a charged species that changes direction, that's called an acceleration, and an acceleration gives rise to an emission of radiation? So because the angle of deflection-- so this is low-angle deflection, this is high-angle deflection. So low-angle deflection means low energy emission. High angle means high-energy emission, and the result is this continue spectrum that I've shown you here. So this is the result of low-angle scattering of the ballistic electrons. This is the result of high-angle scattering of the ballistic electrons, and somewhere in the middle here is the dominant angle.

I can't calculate this curve with one exception. Imagine the electron comes from the cathode, and with all of its energy is dead on and stops, gives up all of its kinetic energy to a photon. That's the maximum amount of energy possible. Let's look at that. That's the case where an electron comes in, stops dead here and then emits the photon. Sp the kinetic energy is translated into the photon energy. So we can do that one. That's a straightforward calculation.

So the energy of the incident electron-- E of the incident electron is equal to product of the charge on the electron and the plate voltage. Well, the charge on the electron is the elementary charge and the plate voltage is whatever it is, and I'm going to equate that with the energy of the emitted photon, and that's equal to hc over lambda. So now I can cross multiply and I can call this the lambda of the shortest wavelength. That's the shortest wavelength on the whale-shaped curve. So by algebra, you're going to get the product of the plane constant times the speed of light divided by the elementary charge times the plate voltage, which turns out to be 12,400 divided by plate voltage where the wavelength's given in angstroms.

Just try it. If you put 10,000 volts, you're going to get 1.24 angstroms, which is smack dab in the middle of the x-region of the spectrum, and this is called the Duane-Hunt Law. That's the only thing we can compute in the continuous spectrum. So I can get this one. Lambda shortest wavelength, because shortest wavelength is maximum energy.

Now there's a fancier name for this whale-shaped curve, and it's the scientific community's term, and it's a German word. It's called bremsstrahlung. I love it. You need to know this. You can impress your friends at parties. What does bremsstrahlung mean? Brems is the German word for brake, as when you put on the brakes of a car. And strahl, strahl is the word for ray. And ung is like ing. So this is raying radiation and this is the radiation of braking.

So the electrons are coming in and when they come up against the negative charge of the outer shell the target atom, they are slamming on the brakes and skidding everywhere. So this is what bremsstrahlung means: braking radiation. So we're going to call-- I'm going to put a B here-- see that? I was thinking ahead. B is bremsstrahlung. OK.

So we've got a lot going here. for us. I think we've explained a fair bit. Now I want to talk about modern x-ray tubes. What do modern x-ray tubes have that these primitive ones that Moseley worked with and Roentgen worked with didn't have? So I want to show you that the modern x-ray tube is the result of improvements made by an MIT alum. His name was William Coolidge, and he's the class of '96-- 1896. And he made a number of improvements.

He actually taught for awhile then eventually spent a good part of his professional career working as a research scientist at the General Electric Labs out in Schenectady. If you go down to the lobby of Building 6, on the south side of the lobby, there's a showcase. Look inside the showcase. You'll see there's a little display in honor of Coolidge. So what's the first thing Coolidge did? He was an engineer so he was thinking about making things more efficient.

First thing he did is he turned the discharge tube into a vacuum tube. Remember, Roentgen worked at low pressure, but there was still gas, and he was blinded by the light and so on. This means you don't get any visible light, and secondly, it's more efficient because if you've got the tube like this with the two electrodes, the feedthroughs and you've got gas inside, some of the electrons are crashing into the gas molecules, and we don't care about the gas molecules. We want to get the electrons crashing into the target. So by going to vacuum, this improves the efficiency. No glow in the visible and higher energy efficiency. More x-rays out per unit power put in.

What's the second thing he did? Second think he did was hot cathode. Remember, you're trying to rip the electrons out of the cathode and send them on their journey. So Coolidge reasoned that if you heated the cathode, you'd weaken the bonds, and the electrons would come off. They'd boil off much more readily, OK? Raise temperature to reduce bond energy, to reduce binding energy of the electrons. The electrons in the cathode makes them easier to boil off. Think I've got a cartoon of that. Yeah, here it is.

So here's the tube lying on its side. So the cathode is over here to the left. It's negative. Here's the anode to the right. That's this purple thing here and the electrons are moving from left to right and so he's got-- see, you can have multiple electrical signals going through the same conductor. It's not the same. You can't have an AC waveform and a DC waveform in the same conductor. So you've got a big DC voltage between the cathode and the anode and you'd got a separate little circuit going through the cathode, running almost like a toaster to make it super hot.

So the potential between here and here is 35,000 volts. The potential along this stretch of real estate might be several hundred volts, and furthermore, this could be an AC signal. It's Coolidge. He was smart. So this makes this hot and now for per given voltage, you get much more yield of the electrons. So that was pretty good. I like that. Smart.

Third thing he did was he heated the cathode and he cooled the anode. Water-cooled anode. Why? You got to dissipate the heat. All these electrons crashing into the anode. You raise the temperature of that anode so high you'll melt it and so they had to run the tubes intermittently. They just get a decent signal. You have to take these x-ray measurements over a long period of time because the amount of x-rays you get is small, but you have to keep shutting the thing down. Otherwise, you melt through the anode. So he put that on a water-cooled copper hearth and was able to run continuous. Continuous operation. No more pulse current.

But sometimes when nature hands you a lemon, you make lemonade. So I'm going to turn this thing around. I'll say, hey, wait a minute. I don't want any water-cooled copper anode. Suppose I want to weld some titanium. Titanium melts at 1675 degrees Centigrade and it's got a voracious appetite for oxygen. Well, this thing's a vacuum tube. So what if I were to take my part and I put the two pieces of titanium in the path of an electron beam and I don't cool the titanium? Eventually, I get the temperature so high that I can weld titanium. This is the birth of electron beam welding. And that's how you weld refracting metals. You get one of those titanium bicycle frames that cost about $4,000. It might be tungsten inert gas. It might be electron beam, depending. So that's the flip side of the technology. By the way, if you were in attendance observing electronic beam welding, what do you think is being generated in the electron beam welding apparatus? X-rays, by the boatload

So there's a fourth thing-- maybe the most important thing that Coolidge came up with-- shielding. You see the yellow here? That's lead shielding. Why did he choose lead? Well, it's got a very high z. That means it's got many energy levels. So that if you start looking at the energy level diagram of lead, you've got lots of action up in here. So what can happen? When the x-rays come with their high energy, the x-rays from the tube on their way out to get you, and everybody standing observing this marvel. They excite electrons inside. So these x-rays are absorbed. The electrons inside the lead rise, cascade down and now they come out. And what's the difference in energy between the x-ray and these? The ones up here are much lower energy. So this is, if you like, a frequency shifter or an energy shifter. So now we're using photons to excite electrons to generate photons. And that's how the shielding works. So you want to absorb and re-emit.

And while we're on the topic, he gave us lead shielding and he gave us beryllium windows because they were using silicate glass, just as you use in your home, but the silicate glass was absorbing some of the x-rays. So to get higher efficiency, he chose beryllium. Why did he choose beryllium? Well, it's got a low z. So that means it has few energy levels. So therefore, there's less absorption and re-emission-- again, higher efficiency.

I think this was taken from one of the other readings. So they flipped it around. See, here you can see the cathode here, the anode. That's one of these things. All right. So the window is up here. You don't use lithium because lithium is unstable in the air unless you had a giant room of humidity set at a dew point of minus 38 degrees, see, and then you can use a lithium window. Otherwise, you use beryllium and lead down here. Why'd he choose lead? Well, you're pretty much at the bottom of the naturally occurring elements in the Periodic Table. So it's the cheapest of all of these heavies. All right.

So now let's take a few minutes and talk about the use of x-rays in characterizing art. So this painting here at once time was arguably one of the most recognizable paintings in the western world. It's The Angelus by Jean-Francois Millet. It was painted at 1857 to 1859 on commission for an insurance company here in Boston. The Boston Brahmins loved BA's paintings of rural life in 19th century France. And this is couple of peasants who are giving thanks to God. The Angelus is a prayer, and they're thanking God for this pitiful bounty of potatoes evident.

Salvador Dali, as an art student, was required to paint this as part of training. You know how when you learn to play the piano, you reproduce the works of the Grand Masters. So when you go to art school, you have to paint. He hated this painting. For many years, it was here in Boston, and then it was repatriated around World War I, it hung in the Louvre, and then ultimately, now it's in the Musee d'Orsay.

In 1963 when Dali was at the peak of his career, he asked the curator of the Louvre if she would have this painting x-rayed. He said this painting spooks him. He doesn't like this painting. And they x-rayed the painting. What did they find? They found that it had been painted over down here. Wasn't an art forgery, Millet himself had painted it over.

You may have heard two years ago there was this art find. It was a van Gogh painting. They found that van Gogh had painted over one of his own paintings that had never been seen before even though the pencil sketches survived, so they assumed that maybe the painting was destroyed in World War II or some such thing. It turns out that van Gogh was so poor at one point that he valued the canvas over the art, and he took his previous painting, and he painted over it. OK. So this was going on here. This is the truth. Now my speculation begins.

So what was underneath here initially? It was the casket of a baby. Look at the pose. These people don't look like they're happy with their bounty of harvest. They're grieving. This was this futility of peasant life. It was a hard life and they lost their baby. So imagine Millet paints this, puts it on a boat, it comes over to Boston, they unveil it, and the directors of the insurance company go, we can't hang this in the lobby of an insurance company. That's my speculation. It didn't take him three years to paint this thing. I think it spent most of its time on the boat. They sent it back and said fix it. So he put the basket of potatoes. That's my theory. All right, look at the pose. This is from the Galleria Borghese in Rome. I was there about two years ago and saw this and went, wow, referential. You see, everything's been said. All of art has been said. Now we're just recasting it.

So now here's Dali's revenge. Now this is what he paints. You see the man is shorter than the woman. His hat is down a little bit below the waistline. There's all sorts of psychosexual things going on here, but we're running out of time. So here's Dali and his father and his dad is saying, see, this is life, et cetera, et cetera. So you can see the reference. See, man taller here, woman taller, et cetera, et cetera.

Have you seen this one? The Hallucinogenic Toreador. OK, he went outside one day in Manhattan to buy some pencils. There was a company called the Venus Pencil Company, you see. And so he came back and made this trompe l'oeil. So this is the toreador. Do you see the breast here is the nose? There is the face. There are the flies of the Thames and here is the cape and so on. Symmetry plane-- all of those Venuses facing back, these Venuses facing forward. There's the bull. The life force of the bull is a crystal. What is the crystal structure? It's one of the 14 Bravais lattices. If you ignore color, it's simple cubic, isn't it? And if you don't believe me, check. And if you don't appreciate it, study. Here's the symmetry plane. Atoms, atoms, fly, fly et cetera, et cetera.

What else do we have here? Oh, this is the one he painted on the occasion of the revelation of the structure of DNA. It's hard to see, but over here is the double helix of DNA. This is his wife Gaia and here are people standing in cubic arrays with guns pointing at each other. And the point that he's making is that now that we've discovered the instruction set for reproduction of life, not just human life, but life, we are still at a point where we can't resist killing each other. So this was the point and he chose to use cubic arrays, and I would venture to say this is simple cubic. If you put a fifth person here, it would be-- are you ready for this? Body-centered cubic. Oh, yes! And there's more, but I think we're running out of time so I think at this point we will dismiss the class.