PROFESSOR: Time to learn. Time to get back to business here in 3.091. So let's do the announcements first. Tomorrow quiz one, based on homework one. Ten minutes. Bring your Periodic Table, your table of constants, something to write with and a calculator. There's about a dozen or so copies of the text on reserve at the Hayden Library. I want you to be aware of that.

Now some of you approached me last day and said is it true that we have to memorize the Periodic Table? Yes. But not the whole Periodic Table. I know some of you are going to say, well that's so 19th century, rote learning and so on. To which I say, you're wrong. Every educated person should know that potassium lies under sodium, which lies under lithium. And you are going to be educated whether you like it or not.

But this is a lot to learn and so we're just going to look at the main block. We're not going to ask you to memorize the lanthanides, actinides and the super heavies. We'll leave that out. So it's quite straightforward. We've been doing this for many years. This is from 2004. And it's not that hard. I give you the blank here. And I even put the numbers on for you. And all you have to do is add the two-letter or one-letter symbol. You don't have to give me the full name of the element. You don't have to get me its density or its electron affinity. You've just got to put argon, in there. Ar. That's all you've got to put in there. OK? And every year people grouse when I announce this. But you'll find out that you'll breeze through it. You'll have 10 minutes. This will be on September 24.

So next week there will be two minor celebrations. One on Tuesday and one on Thursday. So it's going to be a very festive week. And people blast through it. It's one mark off for every error down to zero. We don't give negative scores. And people just go right through it. And then they urge me to make sure that in future years I victimi-- I mean I ask students to continue this. People are very proud of the fact they know the S, P, and D blocks of the Periodic Table by memory.

But I don't want to neglect, disrespect the lanthanides and actinides. So we're going to have two contests. Mnemonics to help remember the names of the lanthanides and actinides. That's tricky to remember. So these are mnemonics contests. So here are some examples. Here's one, see lanthanum, cerium, praseodymium, neodymium and so on, all right? Obviously this one came from industry because of the slur against the Academy. Obviously, somebody in industry has no idea how hard we work here. And plus, look at this: "to dramatically help". This gigantic split infinitive. Clearly, clearly someone from industry.

Here's another one that would help you memorize, I think. Now, this is obviously not referring to 3.091. It must be referring to some other chemistry professor here. I'll let that go unchallenged. Now, occasionally people ratchet up. And this was about six, seven years ago, a young man by the name of Blake Stacey, who was aware of the fact that there are 14 lanthanide elements because there are fourteen F electrons. And an Elizabethan sonnet has 14 lines. And so he took Sonnet 57 by Shakespeare in reference to the fact that lanthanum is element 57. And he wrote this in reference to Sonnet 57. And, of course, he knew he was going to win when he made samarium the word smelting, and being the chemical metallurgist I am, he had me at the fifth line. Actually, I showed this to Professor Sonenberg in Humanities, and she said, actually, this is pretty good. That's one of those times you look at and say, you wouldn't see this at Harvard.

So now I'm going to show you one. Sometimes people ratchet up. A couple of years ago, there was a video. So let's take a look at that one.

[VIDEO PLAYBACK]

PROFESSOR: And she goes through various poses as a superhero of different elemental value.

[END OF VIDEO PLAYBACK]

PROFESSOR: But we don't have that much time. So anyways, September 25, 5:00 p.m. Eastern Daylight Time. Submit your entry, whether it's the big canisters of the Hollywood footage or whether it's just a 14-line mnemonic device. And the prizes-- it's a contest, there are prizes-- I have ties and scarves from the American Chemical Society.

[LAUGHTER]

PROFESSOR: What are you laughing at? These things! Now look at me! This is going to be stylish. They're black. They've got elements from the Periodic Table on them. Very hot. Very hot. They're black. They look great. And we're going to present them on the Friday of the parents' weekend because the parents eat this stuff up.

So now I think it's time to get back to learning. So last day we ended with the stoichiometry, and I showed you the Kroll process, how to make titanium. So the question that we never got to was how do we tell that magnesium has a higher affinity for chlorine than titanium does? How do we know that magnesium is going to reduce titanium tetrachloride to a sponge? So for that we have to look inside the atom. We have to look inside the atom. So that's what we're going to start doing today. And we're going to begin, as often we will, with a history lesson.

So let's go back for a status report around the end of the 19th century. So what did we know towards the end of the 19th century? The atom is electrically neutral. The negative charge is carried by electrons. We knew that there was some carrier of negative charge. We knew further that this electron is very, very tiny. Small mass. And so if it has a very small mass, then by difference, then the bulk of the mass of atom must be contained in the positive charge.

So now the question is, what is the spatial distribution of charge inside an atom? You might say, well why do we want to know that? Well, we're trying to get a physical model of the atom so that then we can start to address the question of chemical reactivity. So we have got to know where all the players are before we can attribute action to them. So let's now take a look at models of the atom.

For the first modern model of the atom we go to J. J. Thompson. J. J. Thompson, he was a professor of physics and director of the Cavendish lab at Cambridge University. The other Cambridge. Cambridge University. And this Cavendish Lab was named after Henry Cavendish. The same one who is credited with the discovery of hydrogen in 1766. He never married, and when he died he bequeathed this fortune to Cambridge University, and they took that money and established a physics laboratory, which is still in operation to this day.

So what did J. J. Thompson tell us? He said the electrons were distributed throughout a uniformly charged positive sphere of atomic dimensions. So that's the text. Now let's make this cartoon, because that makes more sense. Visualize it a little bit better. So it looks a little bit like this. So here's a sphere of atomic dimension. Electrons are these tiny little things distributed throughout the positive sphere. And this is massive because the electrons have very, very low mass. And just to be clear, there are no protons. No protons. So this isn't positive. It's a positive chargeness. It's just a big positive blur. And then the little electrons inside. So the electrons are negative, and they're tiny and low-mass, and they're mobile. He didn't say much about how they move, but you can imagine that they move, and maybe they even spin. And so on. And this was known as the Plum Pudding Model.

There's a big cultural bias here. So even though I grew up in British Canada, I never had this stuff. But my understanding is plum pudding is this dish that's served at holidays and Christmas-time. So the custard is the charge, the positive charge. And these little bits of fruit are the electrons. And they're throughout. At Christmas-time, they might even put little charms in here. Like a little wishbone or something for good luck. And you pull it out and all that kind of stuff. Yeah that's merry, old England.

So this is the Plum Pudding Model. And that's what was in place. By the way, we've been using the term electron, but J. J. did not like the term electron. Actually, he won his Nobel Prize for the-- quote, unquote-- the discovery of the electron. Just as Cavendish didn't discover hydrogen, he characterized it. J. J. Thompson characterized the electron. What did he in particular characterize? He characterized the charge-to-mass ratio. He made the first quantitative measure of the charge-to-mass ratio of the electron. But he never used the term, electron. He called it the corpuscle. He called it the corpuscle of electrical charge, whereas this is really sort of an elementary charge. The corpuscle.

And fortunately there was another British chemist. In fact, he was an electrochemist. His name was John Stoney, who, while I think that Thompson was a brilliant man, I wasn't crazy about his literary choices. And it was Stoney who said, let's call the term electron, coming from the Greek term, *elektra,* which is the Greek word for amber. And you know if you rub amber, you'll build up static charge, and so on. That's where we got the electron from. So that looks pretty good. So that's our theory. And what happens next?

Well, what happens next is that we've got to put this theory to the test. And the person who puts the theory to the test is a man by the name of Ernest Rutherford. Rutherford was an interesting character. He came from New Zealand and he was born on a farm. It was a family with 12 children. You notice Mendeleyev came from a family of 14, this guy comes from a family of 12. So you learn how to survive. He worked on a farm so he was very handy, and that came in to play as his career progressed. He was a brilliant experimentalist. He was able to do experiments where others failed.

And he did this experiment where he was a professor of physics at Victoria University in Manchester in the UK. Now, he came out of New Zealand, got a scholarship to study at Cambridge University. And he was actually a research student for J. J. Thompson. And he conducted his thesis research under J. J. and during that time his thesis research was about the properties of charged particles. And they were very interested in gases and radioactive elements, ionizing radiation, the whole thing. The Cavendish lab was a beehive of activity.

And what he did under his PhD was he understood both the alpha particle and the beta particle. First, he identified what they are. The alpha particle was determined to be the helium nucleus. So this is helium that's lost both of its electrons. So it's just protons and neutrons in the nucleus. Completely naked. No electrons.

And then the beta particle, which other people in physics had been referring to this mysterious beta particle, he made the connection between the beta particle and the electron. So the same electron that's over here and attributed to the negative charge within the nucleus is also a free particle that can go through space.

And these are taken from your reading. And you can see that if you send the particle beam through a charged plate, the negative plate here being the lower plate, the positive particle, which in this case is the alpha particle, will bend down towards the negative plate. And the negative particle, being the free electron, is bent in the opposite direction. So these are the kinds of experiments they would do. And they also looked at their ability to penetrate different media. So when it comes to their ability to penetrate solids, they differentiate themselves. So they alpha particle is quite poor at penetrating solids.

So you see in the cartoon there, the alpha particle is stopped even by that little sheet of paper. So it doesn't do so well here, whereas the beta particle, the electron, can go zooming right through the paper and is stopped by the lead. And then over here they were also studying their ability to ionize gases. So if you take a gas and you bombard it with alpha particles, will you get a lot of ionization? Yes or no, et cetera. And what they found was that it was a complementary, that the alpha particle is pretty good at ionizing gases, whereas the beta particle is poor at ionizing gases, and in fact, is stopped. This is why, if you have an electron beam you need a vacuum. Otherwise, the electron will be dissipated in very, very short order.

So after doing this work with J. J., he got a teaching job in Canada at McGill University up north. And while he was there he continued to do work on the origin of alpha particles and won the Nobel Prize for his work while he was at McGill. And so when he determined that the alpha particle origin in the decomposition, the disintegration of elements.

And believe it or not, in this work back in 1906, 1907, he was already anticipating nuclear fission because he was saying that if you put thorium or polonium into a tube, you can expect that it will emit alpha particles. Well, conservation of mass says they have got to be coming from somewhere. And if they're not coming from out here, they have got to be coming from inside. This was brilliant work. This is Rutherford, young man in Montreal, gets the Nobel Prize in 1908. And then he goes to Victoria University, and he sets up this experiment. Critical experiment. I mean, imagine this guy. I mean, he's already got the Nobel Prize. He could just put his feet up. No, he keeps going.

So this is the experiment. It's called the Rutherford-Geiger-Marsden experiment. Because Rutherford was the brains behind it and Geiger and Marsden were the guys in the lab. And so here's the experiment. So what he's going to do is he's going to put this model to the test. We're going to see if this model makes sense or not. So he's got a gold foil-- now they used different elements, but ultimately they loved gold because gold, first of all, is noble and it doesn't oxide. So it's pure, even in atmospheric oxygen. And secondly, we've known since antiquity we can physically deform gold and make it into something sub-paper thin.

So that's what they did. They beat this thing down to 600 nanometers thick, 0.6 micron. And they used alpha particles here. Radium, polonium, thorium as the source in the lead container and so on. And this stream of alpha particles comes zooming out at energies of 7.68 million electron volts per particle. So this is like a cannon with a pumpkin in front of it. And they're going to shoot these at the foil.

So what's the purpose here? They want to see what's going on. And if you imagine that we are shooting alpha particles, which are positive, and I've got a wall here of all of these nuclei that are essentially positive chargeness, uniformly distributed with these tiny, tiny little electrons of almost no mass, you'd expect that most of these particles are just going to go zooming on through. Beyond a certain thickness, I might start seeing some attenuation. But if I get the gold film really thin, I should just go blasting these all through.

Well, what they find is, two things. First of all, most of the particles do go through. When they go through, they're deflected a little bit. They don't just go through, they are deflected. And most of them are deflected through low angles. But a small number of them are deflected through high angles. They almost go straight back at the source. So if you've got that set of data, that doesn't support this model. This model cannot be sustained in the light of those data. It's a very important experiment.

By the way, how do they count these things? Well, Geiger is the same guy who give us the Geiger counter. Geiger was a technician that worked for Rutherford. And he developed this screen, they called it a scintillation screen. It was coated with zinc sulfide. And so when alpha particles bounced and they hit the screen, they would excite electrons in the screen and then cause a scintilla, a spark. And then what you do is you just get a graduate student or some other source of abundant, cheap labor-- and you have a whole bunch of graduate students sitting here-- and they count. That's how it was done in good old days, 1909. And so they counted what the distribution was. So that's the experiment.

So this is taken from your book. So this what you'd expect. And this is what they saw. So this is small angles and this is large angles. Theaters of the angle here.

Now Marsden, who's the third? There's a third person. Marsden. Marsden's not too different from you. Marsden was about 20 years old at the time. He dropped out of school and then he came to Rutherford, and he said, I'm looking for a job. In those days, you couldn't return to college. If you dropped out, finished. You had to stay all the way through. Once you dropped out, they slam the door behind you. But Rutherford, he was different. He looked at people on the basis of their intrinsic value. He didn't care about title.

And so he said to Marsden, OK, you want to do something for me? Here's your question, I like you to imagine an alternative model of the atom. And here's the alternative model of the atom. What Rutherford said was, suppose instead, if this is the dimension of the atom, instead of having positive charge uniformly distributed, he said, what if we have positive charge concentrated at one point and then out here we have the negative charge? So here's the positive charge. And here's a whole bunch of negative charge. And now here's the next one. And here's the next one. And so on. And now we're going to shoot these helium nuclei. See what's in between here? This is a void, taking from Democritus.

And so now if I shoot the positive helium nuclei here, if they get close to this positive charge they'll be deflected. If they don't get close to the positive charge, they just go right through. And once in awhile they get almost on axis, in which case they fling back. This model would be consistent with the data set I just showed you. And then to go further, he says to Marsden, I'm going to tell you what the distribution of high-angle scattering was, you tell me what is the ratio between the radius of the nucleus, where the positive charge is to the-- excuse me, I'm showing you the diameter, so this is the diameter of the nucleus versus the diameter of the atom. What would be the ratio of the two?

I mean, it's gold, so I know I got 79 plus here. And I've got 2 plus. And I've got a 79 plus. What would be the size of the sphere of 79 plus that would deflect something of 2 plus through this angle? So that's Marsden. It's not bad for a kid that's been out of school for a couple of years. That's his problem. So he did. He did the calculation. He did the calculation and Marsden figured out that the radius of the nucleus to the radius of the atom is on the order of about 1 to 10,000.

That means most of the gold foil is void. Most of the gold foil is nothing. And you've got all this mass, highly dense, concentrated here. So this is the Rutherford model, which was called the nuclear model. This was proposed by Rutherford because it has such a thing is a nucleus. He coined the term, nucleus. So that's a big step forward from this thing here.

So you'd think that the physics community would be ecstatic. That now we've got a model that squares with the data. Well, what do you think the reaction to Rutherford's announcement was? Condemnation. Derision. People didn't like it. They laughed at him. They said, well, this is crazy. There's a couple of problems with this. So strong negative reaction to Rutherford's model.

And here the two major objections that people posed. First of all, they talked about nuclear collapse. They said if you've got a system of negative particles revolving around a positive nucleus, electrostatic forces are going to cause them to be drawn to one another. What's going to keep the electrons from collapsing into the nucleus? That was the first objection. Coulombic attraction.

Coulombic, electrostatic, same thing. If you want to use a man's name, Coulombic. If you don't want to use a man's name, electrostatic. Coulombic attraction between plus and minus.

And the second one was, OK, suppose for some reason we don't understand that the electron doesn't collapse, it stays in orbit, it's still not going to work. Because you run out of energy. If you take a charged particle, a charged particle that accelerates consumes energy. Acceleration, as you know, can mean either change in speed or change in direction. So if the electron is revolving at a constant speed, it has to change direction; otherwise, it will fly out of the room. So changing direction means acceleration, which means what keeps the energy in the electron? Why doesn't the electron just run out of energy and just stop? Even if you can prevent it from collapsing, it will just stop. So this is the problem of energy deficit. Energy deficit. Well, what powers the electron? What powers the accelerating electron? So that's a problem.

So now the story continues. The next chapter is 1912. Because this is 1911. In 1912, a young Danish businessman by the name of Niels Bohr. Niels Bohr just finished his PhD in Copenhagen and he got a fellowship from the Carlsburg Brewery Foundation. Carlsburg Brewery put up money for science. So he won a Carlsburg fellowship. And he was a young physicist. And he knew that in the UK there was a controversy brewing between the model of Rutherford and the model of J. J. Thompson. So he says, you know what I'm going to do? I've got a year, I got money. I'm going to spend six months with J. J. Thompson, I'm going to spend six months with Ernest Rutherford. And that's what he did.

So he goes and he spends six months at the Cavendish lab with J. J. and then he goes up to Manchester and he spends three months at Manchester with Rutherford. Why didn't he spend six months? Because he got a job offer and he went back to Copenhagen to start his teaching duties. And what he did is he developed a quantitative model for us. He developed a quantitative model. And that's all part of what I showed you the other day. We recognize patterns. That's what the Rutherford, Geiger, Marsden experiment gave us. The pattern of the distribution of alpha particle deflections.

So now we need to develop a quantitative model that will explain the observations, and if it's a really good model, it will make predictions that, again, can be tested by experiment. So we ratchet back and forth between experiment, model. Experiment, model. So he proposes the model, not with J. J., because J. J., I don't know what he did there. This is where he wants to propose the model. Quantitative model. To Rutherford's atom.

Let's take a look at what we've got there. Now, big lesson here. How do you announce a model? You don't put an ad in the newspaper. This is the scientific literature. This is not Google. This is not Wikipedia. This is a primary source. This is how science is communicated. So this is a journal. It's called *Philosophical Magazine* and *Journal of Science.* It goes all the way back to the 1600s.

In fact, when I was a freshman at the University of Toronto we had copies of *Phil Mag* going back all the way to the 1600s. And these were not facsimiles, these were real copies. And I was in the stacks and I was reading something by-- I don't know-- Lord Kelvin, you know late 1800s, and I said gee, well, if I've got Lord Kelvin, then maybe I can go over here to the early 1800s and read Humphry Davy and, gee, if can keep going, and going and I pull out a leather-bound edition of *Phil Mag* from the 1660s, and I open the book and there's a paper about gravity by Isaac Newton. And that's how science is communicated. So I urge you to go to the library and read primary sources. Most of this stuff is available online. You can just sit at your desk and you can zoom in to history.

So this is *Phil Mag* and this is London, Edinburgh and dublin. See this is 1913, so Ireland was not a free state yet. So Dublin was a British city. London, Edinburgh, Dublin. There's a close-up of it. July 1913, *On the Constitution of*

Atoms and Molecules by Niels Bohr, Doctor of Philosophy, Copenhagen. And it was communicated by Professor Ernest Rutherford, FRS, Fellow of the Royal Society. So, let's read. It's in English.

In order to explain results of experiments on scattering of alpha rays by matter, Professor Rutherford has given a theory of the structure of atoms. You see the dagger here? Down here, Ernest Rutherford, *Phil Mag,* duh-duh-duh-duh. There's a citation. See, attribution. According to this theory, the atoms consist of a positively charged nucleus surrounded by a system of electrons kept together by attractive forces from the nucleus. That's what keeps them from just fleeing anywhere, and they don't go in, but they vwomp. The total negative charge of the electrons is equal to the positive charge of the nucleus.

Further, the nucleus is assumed to be the seat of the essential part of the mass of the atom and have linear dimensions exceedingly small compared with the linear dimensions of the whole atom. This is beautifully written. Clear. It's textbook quality and it's written by a man whose native language isn't even English. Read the literature.

The number of electrons in an atom is deduced to be approximately equal to half the atomic weight. Great interest is to be attributed to this atom model. You have to know a little bit about Bohr. Bohr used this phrase, great interest. That was his way of saying, embroiled in controversy. If someone said something that he didn't agree with, instead of saying, I think that's nonsense, he say, very interesting. Very interesting. So great interest is to be attributed to this atom model. That means people are in pitched battle on both sides. For as Rutherford has shown, the assumption of the existence of nuclei as those in question seems to be necessary in order to account for the results of experiments on large-angle scattering of the alpha rays.

Another footnote: Geiger and Marsden. Geiger and Marsden published their results in this journal. In an attempt to explain some of the properties of matter on the basis of this atom model, we meet, however, with difficulties of a serious nature arising from the apparent instability of the system of electrons. Difficulties purposely avoided in atom models previously considered. For instance, in the one proposed by Sir J. J. Thompson, which is to say, mmm, you know, it's curious. You condemn the Rutherford model because he's got electrons in motion, which means they're accelerating in energy deficit. But in the Plum Pudding Model, the electrons are in motion, and J. J. Thompson is silent about it.

So this is a very aimed barb right at J. J. Thompson done elegantly. With this elegant slap in the face. You know this is how scientists do it. They don't go, oh you're ugly , and your mother dresses you funny. Instead they write things like this, difficulties purposely avoided in atom models previously considered for instance. So this is sort of yeah, how about you, huh?

But anyway, we can go on and on. But down here, the result of the discussion of these questions seems to be a general acknowledgment of the inadequacy of classical electrodynamics in describing the behavior of systems of atomic size. So he's saying that you can't use classical electrodynamics down to subatomic dimensions. He's saying that those models, any more than you can use planetary models down to human dimensions, this, in many respects, is foretelling nanotechnology. He's saying the properties we know, of how things behave in the Newtonian world are not necessarily valid at atomic dimensions. This is very important stuff.

Anyway, so what I did is I went through the paper and I've reduced the content of the paper to these things called postulates. So Rutherford's atom is correct. That's the first thing. Classical electromagnetic theory not applicable to the orbiting electron. And you're going to get-- the PDF and all this is going to be posted, so don't feel like you have to be a super stenographer here.

Newtonian mechanics is applicable to the orbiting electron. So you can see, wait a minute it's sort of like cafeteria physics here. Electrodynamics doesn't apply, Newtonian mechanics does apply. And the answer is, yeah. That's what we're going to do here. We'll build a model and we're going to try these ideas out. And if they're crazy, how are we going to know they're crazy? Because there's going to be data that refute. But if we get data that supports all this, then there's only one conclusion. This thing makes sense up to a point.

The energy of the electron is conserved in the system. It's bond is kinetic plus potential. The quantization through angular momentum. And lastly, the Planck-Einstein relation applying to electron transition. So now I'm going to take all this and I'm going to write out the model for you. Now, I don't want you to say, oh, he's going to derive something. Do we have to know derivations? This is the only time I'm going to derive something for you. The reason is, it teaches the model. It teaches how the model is based on assumptions and so on. But I don't expect you to memorize things because that's not the way things work.

So let's go starting with this point here. This point here is Bohr model atom. So it's Bohr's representation of the Rutherford model. We can call it a nuclear model or a planetary model. Because you've got orbiting electrons. Now, first important point. The Bohr model is the simplest model. It works for a one electron system. So he has a single electron. Planetary model, single electron. And this orbits the positive nucleus.

So you might say, one electron, well, what's that mean? Well, obviously it means atomic hydrogen. But it could mean helium plus. That's a one electron system. It could mean lithium 2 plus. It could mean roentgenium 110 plus. That's a one electron system. And this is all gas. Gas phase. No solids here. Gas phase. So it's an isolated nucleus with one electron around it. That's how we're going to begin. And here's what it looks like. I'm going to put the nucleus, first of all not to scale, because we're not going to draw 10,000 to 1. Over here is the nucleus with z positive charge. And then out here is the electron in orbit. This is the lone electron in orbit. And this distance is r. The distance from the nucleus. You're going to say, well, is that from the outside or the inside? It's 10,000 to 1; it doesn't matter. Forget about it.

So now let's use this concept. We're going to say it's a conservative system and so the energy of the system is simply going to be the energy of the electron. You might say, well, why don't you consider the energy of the nucleus? Because the nucleus is, relatively speaking, stationary. To use Rutherford's colorful language, he says when an elephant has fleas, it's the fleas that do the jumping. So you don't care about that energy of the nucleus in this case. So the energy of the electron is the kinetic plus the potential. So the kinetic energy, we're saying it's 1/2 mv squared because it's Newtonian mechanics apply. See number 3. So that's 1/2 mv squared, where v is the velocity.

So that's the kinetic, and then what's the potential energy? The potential energy here is electrostatic. Because that's the energy that's stored here is due to the Coulombic forces between them. So that's going to be q1, q2 over 4 pi epsilon 0 divided by r. So what I'm going to do here, we have to just for convention I'm going to always choose that q1 in my derivation, q1 will be the charge on the nucleus. so q1 will equal z, which is the proton number here, times the elementary charge. Remember e is the elementary charge. It's not the charge on the electron. So sometimes I use the word e with a minus sign, meaning the electron. But this is e meaning the elementary charge. z times e and then q2, which is the charge on the electron, is minus the elementary charge e. So we're always going to have minus e out here. What varies is z.

And so we're going to make some substitutions. So this is going to be what? It's going to be 1/2 mass of the electron times velocity of the electron squared. And now q1 is ze and q2 is minus z, so that's minus ze squared. And then that'll be over 4 pi epsilon 0 r. And I'm going to call this thing equation 1. And by the way you can find all of this information by looking at your table of constants.

So see, epsilon 0 sitting here. Permittivity of vacuum. There it is, 8.85 times 10 to the minus 12 farads per meter. Elementary charge 1.6 times 10 to the minus 19 Coulombs. Electron mass, 9.1 times 10 to the minus 31 kilograms. And what's this 4 pi epsilon 0 doing here? Well we know this is going to give us joules. And this is going to give us joules. And the epsilon 0 is the factor that renders electrostatic units on to the same plane as mechanical units. If I plug in-- this is going to be Coulombs, it's Coulombs squared, and this is going to be meters, and now this things is farads per meter. And I got farads per meter times meters divided by Coulombs squared. I don't care. This, with impunity is joules.

Because this is an energy unit. And this is Systeme Internationale. And this is kilograms times meters per second, meters per second and how many apples in a bushel and-- forget it! Put this in kilograms. Put this in in meters per second. With impunity, it's in joules. So that's what that thing does there. Alright. Good. So let's keep going.

Postulate 3. Newtonian mechanics applies to orbiting electrons. So orbiting electron, it's in a stationary orbit. So that's the thing. So postulate 3 implies that the sum of the forces acting on the electron must be 0. This is a force balance, right? If the forces are out of balance, the electrons are either going to move closer to the nucleus or move farther from the nucleus. So that's equal to, again-- it's a sum of a dynamic force and a Coulombic force, or electrostatic.

Here I just noticed a nice parity here. So these are technical terms, but we can give them human terms. So the dynamic force, there's a Newtonian force, this is a Newtonian force and this is a Coulombic force, after the two people that are associated with the ideas. Charges interaction are Coulombic, blah, blah, blah, blah.

So now lets substitute in. So we know that if you've got something orbiting, something tethered, then the dynamic force on that, that pulls the object away on a tether is mv squared over r. And the electrostatic is q1 q2 over 4 pi epsilon 0 r squared. Force goes as 1 over r squared. Energy goes as 1 over r. How do you know? Well, one way to think about it is, you know energy is the result of a force moving through a distance. You say, I'm working really hard, and I say I don't see any force moving through a distance. That's a joke.

So here's energy. So force. So if this is 1 over r squared, the integral of 1 over r squared is minus 1 over r. If you get these backwards, you integrate 1 over r, you're going to get natural log of r, which makes no sense. That's one way. Or the other way is, you can just remember. So anyways we're going to plug into those values. And what do we get? What we get there is this. We get mv squared over r. q1 is z times e. q2 is minus z. So it's minus ze squared over 4 pi epsilon 0 r squared. And I'm going to call this equation 2.

So now we keep going. Next one, energy quantized through its angular momentum. This is really critical. This is the major breakthrough by Bohr. Now what do we mean by quantization? I told you that in 1909, Millikan had figured out that electrical charge is quantized. Now quantization had already been annunciated by Max Planck in 1909. You see, the classical theory of radiation gave this prediction for intensity as a function of wavelength. They called this the explosion, the collapse of the theory. As you go to low wavelength, the intensity goes without abatement. But these are the spectra that were measured. Depending on the temperature of the gas, you get this distribution. So how to get the distribution to turn around at lower values of wavelength? And in order to do that, Planck suggested that light is composed of energy packets, or quanta. That light is a stream of individual energy bits. And the elementary unit of electromagnetic radiation is the photon.

And you can say, well I don't understand, where goes he get that from? That's not the way to think about it. Say, if you make this assumption you get these curves. And then figure out what it means. You can't make everything anthropomorphic. If this were the case, and furthermore if the energy of one of these quanta was related to its frequency-- and wavelength and frequency are inversely related-- then the proportionality constant is h, which we now have designated the Planck constant in honor of Planck, then you get this.

People grew to accept it. 1900, he gets a Nobel Prize for it. La de da! But who knows what light is anyways. It has no mass, it's kind of mysterious. 1900, the whole concept of action at a distance was strange to people. The notion that something could affect you, from me, without physical contact, this was a new idea. We take it for granted, but this was very new. So it's kind of mysterious, they said, OK, he's a physicist, who knows? And it worked! But it's light.

Now what Bohr is going to say is the electron moving in orbit, he says, I'm going to apply the same concept of quantization to the electron moving in orbit. Well, that's different. And using this value he gives us mvr, which is the angular momentum is quantized n h over 2 pi. h is the Planck Constant and n is an integer. 1, 2 3 4, et cetera. So this is the quantum condition and this will be equation 3. And I have three equations and three unknowns, and what I'm going to do next day is come back and show you the solution of the equations and how they give us a set of equations that allow us to compare with data. So let's jump to the thing. And by the way the Planck constant is there.

Now Niels Bohr eventually won the Nobel Prize. He was widely revered. He achieved the stature on a par with Einstein. If you go to Denmark, it's still not part of the European Union, you can still get the 500 Kroner note if you change a 100-dollar bill there. And there's Niels Bohr with this pipe. And you can see the concept of things rotating around it an so on. There's a young Niels Bohr. This is Bohr with Werner Heisenberg. Heisenberg was a post-doc who worked with Bohr in 1925 and annunciated the Uncertainty Principle, which we will study a few lectures from now. This is a chemical conference sponsored by chemical company Solvay. Brussels 1930, there's Bohr and Einstein. They loved hats. This is the Hamburg, this is Borsalino. Here's Bohr mixing it up with royalty. This is a young Queen Elizabeth of England. There's Prince Phillip. This is the royalty Danish family. Bohr loved music and here is with Louis Armstrong undoubtedly talking about the resonant structures within the tube here and how to get the various harmonics and overtones.

Now last thing, a little bit about hydrogen. We've been studying hydrogen here, the one electron atom. But there are isotopes of hydrogen. The original was discovered by Henry Cavendish. There is one form of hydrogen that has a neutron in addition to the proton. That's the deuterium, from which we can get heavy water, D2O. This was discovered here in New York at Columbia University by Harold Urey. And then lastly, there's a second isotope of hydrogen that consists of two neutrons and a proton. That's tritium and it was discovered at the Cavendish lab by Ernest Rutherford. He was active right up to his death.

In fact, it is argued that Rutherford did his best work after he got the Nobel Prize. Your book is showing this. It's nice to follow. We started with Dalton and now we're here and then later, in another week or so, we'll be down here. And here's the sort of the intellectual road map that takes you to modern atomic theory. So with that I'll dismiss the class and we'll see you on Wednesday.