CATHERINE DRENNAN: Let's try the countdown again. You can just give it to them for now. We'll figure it out later.

I like to ask people to explain, now that they know what the right answer is, if someone will explain why that is the right answer. And I know it's a big class, and people sometimes get nervous about talking. So I bribe people. So today, the person who answers why that is correct will get an MIT chemistry T-shirt. OK.

AUDIENCE: All right, let's see. If you're using 5 moles of N2, you need 15 moles of hydrogen gas. Since there's not enough hydrogen gas-- there's only 10 moles-- that means the hydrogen gas should be the limiting reactant since you would need roughly 3.33 moles of N2 for it.

CATHERINE DRENNAN: Great. And here is an MIT chemistry T-shirt.

[APPLAUSE]

CATHERINE DRENNAN: OK, so you'll notice that the prizes are good in the beginning, get worse throughout the semester, and get good again at the end. So keep that in mind.

OK, so let's try to get started. It's been a little bit of a crazy start. If people are still having clicker problems, we have a couple more clicker questions that you can try out. And we'll get your clickers working by the end of class today.

So the topics-- today, we're going to be talking about the discovery of the electron and of the nucleus. And I said that there's going to be limited amounts-- or every time I have a lecture that has some history, I'm going to counter that with some modern chemistry. So next week, we're going to have two examples of modern uses. But today, we're going to do a little history.

And I like history, especially when it can lead to a cool demo. So you might have noticed something demo-like came in while we were doing the clickers. So that's always good. And I also like talking about history when I feel like it's a great example of a challenge that chemists face, and really, most scientists face, that they used to face and still currently face, which is that chemists study small particles. They study things that are really tiny.

How do you study something that's really small? How do you demonstrate that something that is invisible to the eye actually exists? So this is a common challenge. And so today, I'm going to tell you about how the electron and the nucleus were discovered at a very low-tech time in our scientific history, how they were able to figure this out.

And let me just set the stage of what people were thinking around this time, and how these discoveries really changed everything. So in the late 1890s, chemists were patting each other on the back. And physicists too were thinking, boy, we have it all figured out.

We have a real, complete understanding of our universe. We have atomic theory of matter. We have Newtonian mechanics. This is really great.

And in fact, someone said these words, which are really dangerous words, that our future discoveries must be looked for in the sixth decimal place. So honestly, when I started studying chemistry, I thought everything about chemistry was probably already known. And it was just fine tuning things. I was absolutely wrong at that time. And this statement was absolutely wrong, and it really came right before the major discovery of the electron, where they realized they hadn't really understood anything about the atomic theory of matter.

So more experiments are always dangerous because they can change everything. And that's why I really like science. All right, so the experiment I'm going to tell you today, JJ Thompson's discovery of the electron. Or one of the experiments I'll tell you about today, and this is really a pretty simple experiment.

So JJ Thompson was interested in this thing called cathode rays. He had hydrogen gas, and then he took an evacuated glass cylinder. And he put hydrogen gas in it. And then he applied a current to that, and he could see these rays coming off.

And he thought that was pretty cool. And so he was wondering about these rays. Are they made up of negatively charged particles, possibly charged particles, maybe neutral? What are these things?

So he decided to do this experiment. And he wondered whether if he took two plates and had charges associated with them, whether he would see the cathode rays deflected or not. Well, first, he didn't apply any current, so it was just neutral, just to see if putting these plates in would affect anything in any way. And so when he did that, when there was zero voltage difference between these two plates, he could see the cathode ray hit this phosphor screen. And there was no deflection.

All right, then he said, OK, now, I'm going to charge things up, and see if I can see a deflection. So he did that, and he saw the following. There was a deflection. And so now, the different voltage between the plates was greater than 0. And now, he saw the cathode ray was being deflected a different distance of delta x over here.

And it was being deflected toward the positive plate. So that said to him that the cathode ray contained negatively charged particles. You'll notice that the word "negatively" is the only word on the screen in blue. And if you look at your notes, you'll see that there's a blank spot. Just pointing out there might be a correlation there.

OK, so he knew some things also from classical work that was done in the time. And I didn't reset my boards. So he knew something about what it meant if there was just deflection.

So we had our deflection of the negatively charged particles. And he knew that that was going to be proportional to the charge of the negatively charged particle. And it was going to be directly proportional to that, and inversely proportional to the mass of the negatively charged particle.

So it was a pretty big deflection, so he wasn't sure. Maybe there was a very big charge, or maybe there was a very small mass, or maybe both. So then he wanted to see what happened if he really got things going, and he applied even more of voltage difference.

So he did that. And when he did that, he saw this. He saw another deflection, but this time, it was much smaller. And it was toward the negatively charged plate.

So he realized that, in addition to the negatively charged particle, there was also a positively charged particle. So for that particle, then, the deflection of the positively charged particle should also be proportional to the charge on the positively charged particle, and inversely proportional to the mass of the positively charged particle. But there was a big difference in this deflection. Toward the positive plate, there was a big deflection. And toward the negative plate, it was pretty small.

So he knew that this deflection was much bigger than that one. And then he thought about-- is that going to be due to charge or mass? But he said, the charges should be the same because it's neutral normally. So those charges must equal each other, the absolute values at least, must equal each other. So then we can think about the comparison of these deflections.

So if we can take the absolute value of the deflection of the negatively charged particle over the absolute value of the deflection of the positively charged particle, on the top here, we're going to have the charge of the negatively charged particle over the mass of the negatively charged particle. And the absolute value of that term over the charge of the positively charged particle, over the mass of the positively charged particle.

But now, if you say that the charges are equal to each other, at least the absolute values of them, we can get rid of that term. And just see that the mass then, of the positively charged particle over the negatively charged particle, remains. So if this is going to be big, and we know it is, it's a big difference. The negatively charged particle deflected a lot more than the positively charged particle. That means that the difference in masses also has to be big, and that that negatively charged particle must be a lot smaller in mass than the positively charged particle.

So if we go up a little bit here-- oops. So the mass of the negatively charged particle must be a lot smaller than the mass of the positively charged particle. And actually, it's about 2,000 times smaller. So he was able to figure all this out by just doing this pretty simple experiment.

So he had now a small, negatively charged particle, and also a positively charged particle. And later, the negatively charged particle got a name. The negatively charged particle got the name of the electron. And its mass was determined in an another interesting experiment I won't tell you about. And it was determined to be really small, about 9 times 10 to the minus 31 kilograms.

So through this experiment, he was able to figure out, that in these cathode rays, you had something that was tiny, this electron. And that means this idea that atoms were the smallest thing out there was incorrect. That's what everyone believed. They were patting themselves on the back. They had figured it all out.

But there was something smaller than the atom. There was this electron, this negatively charged particle that was really tiny. So it is pretty cool. It's a pretty low-tech experiment that figured out something that really changed the way that we thought about science.

So what about the nucleus? So we had the electron, and we also had this idea there was something positively charged going on there. And of course, in that experiment, that was H plus. But what about the nucleus?

So Rutherford is credited with the discovery of the nucleus. So this was a little later. And he had been studying radioactive material. And his good friend, Marie Curie, from France would often send him interesting samples for him to study.

I'm not sure quite how they got from France to England. Some of these were really cancer causing things. I don't know how many people touched them without safety precautions on the way.

But anyway, it's interesting to note that Rutherford actually did not die of cancer, despite this research. He was literally the victim of his own success. So after his great discovery of the nucleus, which I'll tell you about, he was made into a knight. And at one point, he became sick. And he needed a doctor.

Well, if you're a knight in England, you can't just have any old doctor treat you. You need to have a doctor that is also a knight. And so while he was waiting for a doctor of the appropriate ranking to come and treat him, he died. So he literally died of his own success. He was a victim of his own success.

But it wasn't just his success as I'll tell you about. He had some help. He had a really good graduate student, a really good undergraduate student helping him out.

So he was studying these alpha particles that were being emitted from this radioactive material. And we know now that this is Helium plus 2 ions. But that was not known at the time. They just knew something was coming out of this radioactive material, and they wanted to find out what it was, and characterize the properties of this.

So he had a post-doc named Hans Geiger. And this is the Geiger of the Geiger counter. And he also had an undergraduate student, E. Marsden. And so together, they did the following experiment. And I wasn't obviously there, but I'm imagining that by "they did the following experiment," it meant the undergraduate and the graduate student, or maybe even just the undergraduate.

OK, so here is the experiment. They had the radioactive material. Alpha particles were coming off, and they had built a detector that would count how many alpha particles were coming off. And so they did the experiment, and they counted.

And they found there were a lot of particles, 132,000 alpha particles per minute, in fact. So then they said, OK, let's see what happens if we put a piece of foil in the path of the alpha particles. And we're going to have really, really thin gold foil. So this is like smaller than a human hair. This is really, really thin foil.

And they shot alpha particles at it. And they counted. And they got approximately-- I don't know how many significant figures-- but 132,000 alpha particles. Seemed to be, in terms of the significant figures, the same.

So it was just going through. These alpha particles were just going through this thin, gold foil. So they had this vision then of the gold atoms being all empty space, and the alpha particles were just going through, no problem. But then they did one more experiment.

And by then, I think this was the undergraduate. So they built this detector. And they had built the detector so it could move. So sometimes when you design something to do something, you actually want to use it for that. So if we have the alpha particles coming this way and on the detector over here.

And it had been sitting, and I've been collecting it. The undergraduate was told, well, put the detector over there, and see what happens. So the undergraduate moved the detector over here. And he said, you're going to see if the alpha particles hit the gold foil and backscatter. So we'll have the detector over here.

So the undergraduate did this. They didn't think it was going to do anything. They needed something for the undergraduate to do. So they had him do that. And then they counted.

And sure enough, click, click. It wasn't a lot, but there seemed to be some backscatter, about 20 counts, 20 alpha particles per minute. That was not expected. They were expecting 0.

So they were detecting backscattering. The alpha particles were bouncing off that thin, gold foil, and coming back at the moved detector. So they could calculate this probability of backscattering, the account rate of the backscattering over the normal count of the particles. And so they had 20 backscattering events, or 20 counts over the 132,000, 2 times 10 to the minus 4, or 0.02%.

This is small, very small. But it was not 0. And I don't know how many times they did this experiment, but I can imagine there were lots of times they did the experiment that no one would really believe this result.

And Rutherford himself said, "it was about as credible as if you had fired a 15-inch shell at a piece of tissue paper, and it came back and hit you." So that's how he felt about it. He was like, I don't understand how this is working. This is so thin. It's like tissue paper, but yet these alpha particles are bouncing off something.

So what did this all mean, once they had repeated the experiment many times? So their interpretation, then, was that these gold atoms were, in fact, mostly empty. It seemed like all the alpha particles were just going through. Most of them were just passing through and not hitting anything.

But there was something in there that could be hit. There was some concentrated mass in this volume that, when the alpha particle hit that directly, it backscattered. And they later called this the nucleus.

So they came up then with this new model, the Rutherford model, where you had mostly empty space. But you had concentrated mass inside that an alpha particle might hit and then backscatter. And Rutherford assumed that the electrons would be in that empty space, and that this positive mass was going to be positively charged. Because he knew the overall atom was going to be neutral.

So just a little nomenclature. We can think about the charge of the electrons in the atom as being equal to minus Z to the e, where Z is our atomic number, and e is the absolute value of the electron's charge. And if this term is negative, then the charge on the nucleus is going to be positive. So we have positive Z to the e, because overall, the atom is going to be neutral.

Then Rutherford went on to actually use this backscattering to measure the diameter of this positively charged, dense part of the atom, of the nucleus. And he was able to measure that diameter as a very small number, 10 to the minus 14th meters. So he did this with this back scattering experiment.

So you might say, how can you get a diameter from this backscattering? And so that's what we're going to try right now ourselves. We're going to do an experiment, and Professor Sylvia Ceyer originally came up with the experiment to do in class. And so she built the first version of this gold foil right here. And originally, she took something apart from her own research program. Since then, it's been replicated so that she doesn't have to shut down her research lab every year when we do this experiment in class.

So here, imagine this as a piece of gold foil. And it's mostly empty space, but there are some small, concentrated nuclei, gold nuclei, these Styrofoam balls. And if we have, over here, some alpha particles, which we happen to have 502 alpha particles. If the alpha particle hits the concentrated part, it should back scatter. Otherwise, it should go through.

So you are now going to be radioactive material. I don't know. Is that the first time you've been called radioactive material? I'm not sure. But we're going to come around. Everyone can have one or two of these.

So let me just tell you. You need to watch your ping pong ball. Once you get it, you can move to the center. Watch your ping pong ball. If it hits the edge of this, it's not a backscatter.

Watch if it goes through or if it backscatters. And you will click in whether you had a backscatter event or not. And from that information, we will calculate the diameter of the nucleus. Do you want to put up the clicker?

I think everyone's good. Do we have any more? OK, everyone, if you want to get up and get a better vantage point, do so. And let the experiment begin. I'm moving out of the way.

OK, so go ahead, and say whether you had 1, 2, or 0 backscatter events. And if your clicker isn't working, we'll ask you to raise your hand and tell us, especially if it was a backscatter event.

Has everyone had a chance to click in? Has everyone clicked in? You can't tell. All right, we're going to countdown. Go ahead and click in, and then we're going to do the calculation.

OK, actually, we need to calculate the actual number of them, not the percent. All right, so we had some backscatter events. So let's see if we can use this information to actually calculate the diameter of the gold nuclei.

All right, so we are going to talk about the probability of backscattering. So we have a probability is equal to the number of ping pong balls backscattered, backscattered over the total number. And this will be related to the radius of those gold nuclei by the following. So we have the probability is going to be equal to the area of the nuclei, the total area over the area of the whole atom. So basically, the piece of foil-- and then that's going to be further equal to the number of nuclei times the area per nucleus, again, over the area of all the atoms, or the piece of foil.

OK, so we know some of this information. So I'm going to move this up. You have an actual number. 36 total? Oh, that's interesting. OK, that's a lot of backscattering.

OK, so we can plug in some of these numbers now. So we have the probability is going to be equal. Someone counted. I didn't count, but someone counted that there were 120 nuclei. And the area is going to be pi r squared. And someone measured the entire frame, or the size of the piece of film, as a 139,000 centimeters squared. Or it was 1.39 meters squared.

OK, so we'll assume that they counted the nuclei to three significant figures. So it's exactly 120. And we'll assume that they measured the box with three significant figures as well. So now we can solve this for r, the radius, or for the diameter.

So if we now solve for the radius, we'll bring the radius over. And we'll have the square root of the probability. And if we take these numbers, and I did the math. I have a calculator, if someone wants to check-- 6.072 centimeters. And then the diameter is going to just be equal to twice that. So we have the square root of the probability times 12.14 centimeters.

And now, we need to calculate the probability. So the probability is going to be the number of backscatter, which was 36. 36 over 502, someone have a calculator?

Someone check my math. Check math for me. Check math, anybody. I don't have another prize. Thank you.

Was it 26 or 36? I can't read up there.

AUDIENCE: You said it's 12 single or double?

CATHERINE DRENNAN: Double.

AUDIENCE: [CHATTER]

CATHERINE DRENNAN: Excellent, checking math for me, here.

AUDIENCE: I can't do math in my head.

AUDIENCE: Yeah, it's roughly 500 [INAUDIBLE].

CATHERINE DRENNAN: OK, 26, and so what does this come out to be?

[? ?]

AUDIENCE: 0.050.

CATHERINE DRENNAN: 0.050, And now we need to plug that in. So we have d equals the square root of 0.050 times 12.14. And what does that come out to be? 2.71-- and the actual was 2.5. Not bad.

So using methods very similar to this, Rutherford was able to figure out what the diameter of the nucleus was. And this was a really important achievement of the time. OK, so in the last few minutes, maybe I'll move this down.

In the last few minutes, I want to talk about the fall out of all of these great experiments and all of these great results. So we now know there is an electron and a nucleus. So there are subatomic particles. What does that mean in terms of what people thought they understood about atomic theory?

So we had this question then. OK, so we have a nucleus, positively charged, and electron, negatively charged. And there's a distance between them. And wanted to know, why do they stay apart? Why does the electron not crash into the nucleus?

So from classical description, we have Coulomb's Force Law, which tells us about the force when you have two charged particles, Q1 and Q2, so the charge on the particles. And you have over 4 times pi times this permittivity constant times the distance, r, squared.

So if you apply a force then, and you have charged particles, if those particles have the same sign, then acceleration should push them apart. The force should be positive and repulsive. So two things with the same charge don't want to be near each other. It's going to be repulsive.

If, like in this case, you have two things that have opposite signs, acceleration should pull them together. And here the force should be negative and attractive. So that's the situation we're in here, positively charged nucleus, negatively charged electron.

So let's consider then a hydrogen atom. It equals one electron, one proton. Let's think about what happens when you have an infinite distance between them.

So if they're infinitely far apart, what is going to be the force? You can just yell out the answer.

AUDIENCE: 0.

CATHERINE DRENNAN: 0, right. They don't feel each other. They don't know anything about each other. They're infinitely far apart. There's no force.

But that's not going to be the situation in the atom. Atoms are small. So they're going to be somewhat near each other. Now, we can think about what happens if they're right on top of each other and are a 0.

And here, we can try out the clickers one more time. OK, so we'll do 10 seconds. Oh, the colors changed.

So most people had it's infinitely attractive. So infinitely attractive, like most chemists, except Avogadro. He's very strange looking.

OK, so if these things are going to be close to each other, then they should be attracted to each other and collapse into each other. So why then are the electron and the nucleus that are infinitely attracted to each other-- why do they stay apart?

So Coulomb's Law is not helping us understand this. But it's really just talking about the force with respect to a distance. It's not telling us anything about what happens when r changes with time. So we'll find in chemistry sometimes that things are spontaneous in one direction, but they're also very slow. So you don't have that the thing doesn't happen, it's just kinetically very slow.

So let's consider time now. Maybe that will help us understand why this is not working. It doesn't, but let's look at that. So what do we know about time? What do we know about acceleration and force in time?

We need a classical equation of motion that can explain how the electron and the nucleus could move under force. So we have our good friend. We have Newton's Second Law. We have f equals Ma, force equals mass times acceleration. So let's think about what this tells us about the electron and the nucleus.

So we can express force as a function of velocity. We can also do that in terms of distance. So now, let's think about what's happening. We know the force. We can calculate the force from the Coulomb's Force Law, the force between the nucleus and the electron.

And then we can think about two different distances, and with that force, how fast the particles should move toward each other. So for the initial distance, we can put take 0.5 angstroms, or 0.5 times 10 to the 10th meters, so that's about the radius of a hydrogen atom. So we take that distance.

And then we want to think about how fast that would then go to 0. And it's fast, approximately 10 to the 10th seconds. Or the electron should plummet into the nucleus in about 0.1 nanoseconds. It doesn't do that though.

So we have these beautiful classical laws. I'm a big fan of f equals Ma. I like all these things. But it's not working to describe what's happening here. So we discovered the electron, discovered the nucleus, but now we have a new problem. We don't understand why the electron isn't plummeting into the nucleus.

So what's the problem here? So is the problem Coulomb's Force or Newton's Second Law? And it turns out, as most of you are probably aware, it's that classical mechanics doesn't work when you consider things on this size scale. So we need a new way to describe what's going on here. Classical mechanics isn't working.

And so we need quantum mechanics. And so that is allowing us to understand the behavior that we're actually observing. We're not observing this plummeting, so there must be a better way to do this. And when you're on this really small scale, you need a different way to describe the behavior.

And so next week, we're going to be moving in, and thinking about quantum mechanics. And if anyone's still having clicker questions or needs a clicker, we'll be down here to help you out. And otherwise, I will see you on Monday.