CATHERINE DRENNAN:

All right. Let's just take 10 more seconds. OK. So let's look at this one.

So first, you want to notice that you have a plus 1 here. So you've lost an electron. And then you want to think about what happens when you start filling the deorbitals. So when you start filling the deorbitals, then the energy changes and 4s and 3d switch an energy.

And so we could write this one either way. We could have put the 3d first and the 4s second. But importantly now, because of that switch in energy, the electron that is lost is lost from the 4s over here. So this has to do with the fact that electron configuration of neutral atoms and ions are different and especially with this 4s-3d switch, that the 3d orbitals drop, change energy when you start to fill them.

And there's really very similar energy between 4s and 3d. And that leads to some of the exceptions that you're responsible to know that there can be subtle things that switch the energy a little bit. So because they're so close in energy, you have this half-filled and full-filled thing where you can pull an electron from 4s and put it in 3d to make 3d5 or to make 3d10. So they're very close in energy. And that leads to some of these interesting features.

OK. So today's lecture, we're moving on to the periodic table. But we're actually talking about a lot of the things that we just talked about. So today actually turns out to be an awesome review for some of the material that's on the exams. So that worked out really well.

In past years, this material was on exam 1. Exam 1 was later. And so if you get old exams from other people, not the ones that are posted, the ones that are posted are mostly old exams, except we were placed questions for material not covered on this exam with material that is covered. So it's not 100% an old exam from this class because we've never had an exam this early before. So there were no good examples.

So if you get old exams from other people, do not freak out when you look at it, and like, oh my goodness. Somehow I haven't learned this. There are today's lecture and also Friday's

lecture we're typically on exam 1. So just keep that in mind. So use our practice exams and then you will not have that problem.

All right. So moving on to the periodic table. This is very exciting for me. And so today, we're going to talk about trends in the periodic table.

We're going to finish that up on Friday after the exam, which will be a clicker competition. And then we're going to go on to talk about bonding of the elements in the periodic table. So that's where we're headed.

So the periodic table, here is one of them that's up here. So this was originally put together a while ago. And it turned out to be amazingly accurate. And this really describes all of the elements.

So this is kind of like the artist's paintbox for a chemist or wordsmiths words. These are all the ingredients that go into making everything. Some of these elements are incredibly dangerous and they're used to make explosives. They're used to make bombs. Other elements here are found in the human body and allow us to live.

All materials, whether it's a desk, a pointer, a bottle of water, everything is made up of elements. So this is one of the reasons why chemistry is so cool because we think about the elements. And elements are made of everything. So we think about everything that makes up everything. And that's pretty neat.

So just to kind of give you a flavor of the joy of the periodic table and introduce you to the elements that make up this periodic table, I feel like we should think about this in music.

[MUSIC - THEY MIGHT BE GIANTS, "MEET THE ELEMENTS"]

[SINGING] Iron is a metal. You see it every day. Oxygen, eventually, will make it rust away. Carbon in its ordinary form is coal. Crush it together and diamonds are born.

Come on, come on and meet the elements. May I introduce you to our friends, the elements? Like a box of paints that are mixed to make every shade, they either combine to make a chemical compound or stand alone as they are.

Neon's a gas that lights up the sign for a pizza place. The coins that you pay with are copper, nickel, and zinc. Silicon and oxygen make concrete bricks and glass. Now add some gold and

silver for some pizza place class.

Come on, come on and meet the elements. I think you should check out the ones they call the elements. Like a box of paints that are mixed to make every shade, they either combine to make a chemical compound or stand alone as they are.

OK. So you get the sense of this. The song is quite accurate. It has lots of information [INAUDIBLE] them.

And it points out some other things like elephants are made of elements. And we're made of elephants-- oh no, wait-- elements. No, it's a really fun, fun song. And it really, I think, expresses why It's so important to learn about the properties of the elements and all the things that you can do with them.

So when it was originally put together, it was put together based on sorting elements by their properties, such as ones over here in column 1 are soft and reactive metals. And it was observed that the elements over here are pretty inert. So they were all grouped together. And later, we have pretty much kept this grouping.

But now, it's really grouped by the electron configurations, which is one of the things you need to know for the exam, how to write these electron configurations. And these reactive metals, it turns out, they only have one valence electron. So they like to react because they want to have a noble gas configuration, so they're very reactive whereas these others that were not reactive, have filled electron configurations.

So they don't want any extra electrons and they don't want to lose them. They don't want to get any. They're very happy as they are. So they're inert. So now these groupings make a lot of sense in terms of the electron configurations.

Now, it doesn't tell you everything. So if you know one element is very safe to consume, that doesn't necessarily mean something right next to it is just as good. And if we consider over here, we consider lithium, sodium, and potassium, sodium and potassium are ions that are really important in the human body. And you have to make sure that if you're exercising a lot, that you keep up the amounts that you're getting. So they're very important ions.

And they will often hang around and serve as counter-ions to other molecules in your body. You have citrate in your body. So you could have sodium citrate where the sodium is hanging out or potassium citrate. But that doesn't necessarily mean that other things will work as well,

like lithium, for example.

But a while ago when 7-Up soda was first put on the market, they thought well, sodium and potassium are a little boring. Let's sort of make things a little more exciting and use lithium citrate instead. It's right there in the same column of the periodic table. And citrate makes things taste lemony, which is a lovely taste. And we'll have lithium as the counter-ion to that.

And so they said this dispels hangovers. It takes the ouch out of grouch. And does anyone know what lithium is used for today? So it's often used for people who have bipolar disorders or manic depressive. So it really did take the ouch out of grouch.

But it's not something that you should just put in a consumable soda. So it has somewhat different properties, even though it's part of that same group. So this is a lesson that I feel like we keep learning over and over again with other things, that you have to be a little more careful. Just because it's hanging out near its friends, doesn't mean it's going to be exactly the same.

All right. So the periodic table is an amazing thing. Let's think about the trends in the periodic table.

So we're going to first do ionization energy. And we've already talked about ionization energy. So this is awesome because it turns out to be a really good review for the exam.

So ionization energy, again, is the minimum energy it's going to take to remove an electron from an atom. And if we just talk about-- just say IE for ionization energy-- we're going to assume it's the first ionization energy unless it is specified. And we saw before that ionization energy is opposite in sign to the binding energy. And so here we have the binding energy of an electron.

And we know that this is a multi-electron atom because it depends on n and l. If it was just hydrogen or one other one-electron atom, then anything with n, all those orbitals, are degenerate. But if you have putting in multi-electrons, then it matters whether you're talking about not just n, but l matters too, whether it's an s orbital or p orbital.

So we've seen this before. But now let's talk more about different ionization energies. So let's look at boron and think about the first ionization energy.

And this is the energy to move an electron from the highest occupied atomic orbital. That's

what that stands for. And it's written out in your notes.

And so what is the highest occupied orbital in this case? Just yell it out. 2p. So let's look at removing an electron from 2p.

If we do that, we go to boron plus. And we have 1s2, 2s2, an electron. And this process, the energy involved in this process, is the ionization energy-- the first ionization energy. It's also equal to the binding energy of the 2p electron. And again, the signs are opposite here.

So now second ionization energy, we just keep going. The next highest occupied atomic orbital is 2s. So if we remove, we get boron plus 2 1s2, 2s1 and an electron. And now the energy difference is due to these second ionization energies. So we say IE2.

And that is equal to the binding energy of the 2s electron in B plus because that's what we're removing. We're moving a 2s electron from B plus here. So we can keep going. We can go to the third ionization energy.

And now we're also going to be removing an electron from 2s. And when we remove the electron, it only had one. So now we have a boron plus 3 1s2 and an electron.

The energy difference is the third ionization energy-- IE sub 3. And this is equal to the binding energy. Or the difference in sign is the binding energy of 2s in the plus 2 system.

So now if we look at this little table over here that's in your handout or this little chart in your handout, you can see that there is quite a bit of difference between these different ionization energies. So we were talking about boron. So here we have the first ionization energy, second ionization energy, third ionization energy, and fourth ionization energy. And so there can be quite a bit of difference in the magnitude of these ionization energies or how hard it is to pull off successive electrons.

And so here are some of the other ones you see when you're going here with boron, you remove the first one here, the second one is about three times harder. We're jumping from p to s. Not too much difference within 2s. But once we get to helium here, 1s2, that's really hard to pull off another electron here. So this fourth one is really big.

And then we can look at these other trends. Beryllium here, we have the 2s and then we go to a 1s. And then we have just the one electron over here for lithium. And then when we come up here, it's a lot harder.

So we can look at these tables and realize these are not going to be necessarily the same. There can be big jumps in ionization energy. And I'm going to come back to all of this and sodium and potassium in a little bit.

But first, let's just stick with boron for a minute and think more about the different kinds of ionization there. So now let's just consider taking a 2s electron, but from two different types of boron-- boron plus and regular boron. So in this first case here, we're going to take one of these two s electrons. And now we have a difference in energy. This is the second ionization energy.

The first one removed the electron from p. So we saw this before. We're moving one of the electrons from 2s. And so this is the second ionization energy. It's also equal to the binding energy of the 2s electron in boron plus.

Now we're going to take a 2s electron. But we're going to do it from boron. So the p electron is still there.

So we go from 2s2 to 2s1 over here. And this energy difference is an ionization energy for a 2s electron. And that's equal to the binding energy of the 2s electron in boron.

So do you think these energies are going to be the same or different? Are they equal? No. So I showed you that little chart and that made you probably think that there is going to be some differences. No, they're not equal.

So why are they not equal? Well, when you have boron plus, you have lost an electron. So you have less electrons available to shield. So you have less shielding in boron plus than in boron.

And if there's less shielding, you're going to have a higher Z effective, less shielding. They'll feel more of the force of the positive charge of the nucleus. And therefore, it's going to take more energy to pull it off. So it's going to be more tightly bound. It's going to be held in because of this less shielding, higher Z effective.

All right. So now let's try a clicker question. 10 more seconds.

OK. So most of you did not like answer 1. But does someone want to explain this?

And do you want to just walk up? Someone want to give an answer why? OK, over there.

AUDIENCE: OK. So if we're choosing between 2 and 3, the answer for number 2, the 3p orbital has two electrons in it. And so the electrons, by nature, kind of repulse each other, right? So it's a little easier to pop one of those two out than if there was only one electron in there by itself and you're trying to pull it out. So yeah, you'd pick 2 over 3.

CATHERINE DRENNAN: OK, yeah. So actually, I don't know if you can take the answer. It's a little hard to read it with the colors on top of it.

But here, you have this plus system here. So you've removed this extra electron. So there should be, you feel, a higher Z effective here, which will mean that it's harder to sort of pull things off.

And let's see this one. There's no way to take the answer down, right? So this one-- oh yeah. OK there, that's better. I can see this more.

So this one here, you're pulling one from the s orbitals here. The p orbital's easier to pull it off. It takes less energy from p than from s. OK.

So let's continue. We'll come back to some of these ideas as we go along because now, we're going to think about how these trends go across the periodic table. So across a row, ionization energy is going to increase. And the reason for this is that Z is increasing. So we're having more and more protons, a bigger Z effective.

You're also adding electrons though. But n, the shell, remains the same. So if Z is increasing, n is remaining the same, what do you predict about Z effective? Is it going to increase, decrease, or stay the same? It's going to increase.

So Z effective will also increase. And if you had a case that every single time you had total shielding of that added electron, then it might stay the same. But you're not going to have this case, this extreme case of total shielding.

So if Z increased, Z effective is also going to increase as you go across. And because n is staying the same, you have more or less the same amount of distance from the nucleus. So you just have this stronger Z effective and it's holding on to the electrons.

Now, if you go down a column, the ionization energy decreases. So in this case, you're also increasing Z. But now you're increasing n as well. And so when you increase n, you have your 3s and you go to your 4's and your 5's. And so now, those other orbitals are way far away and

you have a much bigger effective radius here.

The Z is getting bigger. But it's not really reaching as strongly out. So here, the effect of increasing n is making a much bigger difference than increasing Z.

So going across, we have this increase in ionization energy because Z effective is increasing while n is staying the same or Z is increasing while n is staying the same, which means the effective is increasing. And going down, it's really n that dominates that pattern. So you have a decrease because you're going to higher and higher n.

So let's look at some of those. And we can go back and look at it what I showed you before. I said I'd get back to sodium and potassium here.

So if we consider all these, if we remove one electron, then we're going to go to a noble gas configuration. So with our first ionization when we're over here, we're going to go. And so when we do that, then we say, why are these numbers different for the second ionization? We have a noble gas configuration after we've lost one electron in each case.

But then we can say, OK, well helium is up here, then neon, then argon. So the ionization energy is decreasing as we go down here because n is increasing. So we see that trend in our plot over here.

There's a couple other things that we can see in this plot. So we also see that for boron, this fourth ionization energy is really big. And it's bigger than beryllium's third, which is bigger than lithium's second. So let's think about why that's the case. And that is another clicker question.

OK. Let's just do 10 more seconds. Oops. All right.

I was actually expecting a lower number for this. That's awesome. Right.

So it turns out 1 is true. But all of these other ones are also going to be the same because they've just lost more electrons. So all of them have the same configuration. So that doesn't explain what's going on here.

And this is also true. But binding energies are always negative. That does not explain anything.

So the thing that explains the trend is this one. Even though they all now have the same configuration, it's going to be a lot harder to pull off the electron from the one that has the

biggest Z effective because that's going to be bound more tightly. Great. So you're getting the hang of these types of questions.

All right. So those are some of the trends. And, of course, when there are trends, there is always glitches.

These aren't really exceptions. They are more glitches. And we can rationalize them pretty easily.

So again the trend, increasing ionization energy across, decreasing iron energy down, the increase across as the Z effective increase, and down is the increase in n. But when you actually look at ionization energies, which are often reported in kilojoules per mole, versus Z, you see that it's not just kind of a straight line here. And if we put the elements on here that these correspond to, we see 1s1, 1s2, a drop to 2s, and then we're doing another 2s, a drop to 2p, and then so on as you go up along. So let's look at some of these little glitches. Why isn't this a straighter line here?

So I'm now going to blow up this region on this slide here. And I can just put up this diagram again. And you can see that it's true.

So we're talking about the first ionization energies here. We see lithium is lower then it goes higher then it goes down again. So that's that little trend over here.

So why is this the case? So the ionization energy for beryllium is a bit higher than the ionization energy for boron. And so it turns out that this glitch then is we're going from the 2s to the 2p. And 2p, It's easier to pull off that electron. So that's why you have this lower ionization energy.

We have another glitch over here. Now we're just within p. So what's going on there? And it's very small. It's a very small little difference.

But here, the ionization energy for nitrogen is bigger than for oxygen. So it's easier to pull off an electron from oxygen. And if you draw out your diagram here, is nitrogen where we have obeyed Hund's rules and we put everything in parallel. But for oxygen, we have one extra. So we had to pair the electron.

So it turns out it's a little easier to steal this 2p electron because it's the first one paired. And I kind of think about that as, again, sort of the bus where everyone sits. You can sit two people

per seat. One person sits down, no one else wants to sit next to them until all the seats are taken.

And sometimes when you're sitting in the seat, you're really, really, happy when that person gets up who's sitting next to you. Maybe there's another seat available. They move over to another seat.

So it's often easier to eject the second person from the seat. There's a little bit of repulsion going on there. Everyone's working. They're moving their arms as they're doing their chemistry homework, at least the buses I'm on anyway.

[LAUGHTER]

So that's why there's a glitch there. All right. So this is all well and good. We have our trends. But I always like to think about how do we know any of this is really true? How do you actually measure these ionization energies? And so we're just going to talk about one method for measuring these for a minute.

So photoelectron spectroscopy, PES, is used to determine ionization values. And so you can have some energy that you will use to excite something like neon, which is gas which lights up a sign for a pizza place, and you can inject an electron from it that has a certain amount of kinetic energy. And what you actually measure in this technique is the velocity of the electron. But from velocity, as you know, you can get kinetic energy. And from kinetic energy, we can get ionization energy.

So let's look at this experiment and think about the electrons being ejected. So we have, again, our neon configuration. And we'll lose one electron from p here. And it will have a velocity and a kinetic energy.

We can also think about losing an electron from s. And we're just going to lose one electron per shell here. And we can lose an electron from the 2s and the 1s. And all of those should have distinct velocities and distinct kinetic energies.

So if we measure velocity, calculate kinetic energy, then we can find the ionization energy if we knew the energy that we used to excite the neon. So the incident energy equals ionization energy plus kinetic energy. Or rewritten, ionization energy equals the incident energy or initial energy minus the kinetic energy.

So we can use this to calculate ionization energies. And this should look awfully familiar to you. It's very similar to something that will be an exam 1 where we're talking about using photons and shooting them at metal surfaces and ejecting electrons that have kinetic energy if the energy used to hit the metal is greater in energy than the work function and the extra comes off in kinetic energy. This is basically all the same idea here.

All right. So in this particular case, you would measure three different velocities or three different kinetic energies. And now we can think about what those should probably correspond to using our chemistry knowledge. And some calculations here.

So we have these three different kinetic energies. We know the energy of the incident. So we can do some math.

And when we subtract those, we get one energy of 22. And then this kinetic energy is less. So we're going to get a higher ionization energy of 48. And this is really small. And so now we get an ionization energy of 870.

And so we might not necessarily know which orbitals these correspond to. But if we think about it, you should have the lowest ionization energy to take an electron out of 2p, next would be to 2s, and then the hardest electron to eject would be from the 1s. And these are pretty similar to each other. But this is a much bigger number over here. And so that's kind of consistent with what we know.

All right. So this is how you measure it. And again, this is a multi-electron system.

And so then the energy is going to depend on the two quantum numbers. It depends on l and n. It matters what specific orbital you're talking about.

So let's just think about another problem here. Suppose you had five really distinct kinetic energies. Assume that a very distinct kinetic energy means a different subshell. And so then we want to think about what are the possible elements in the periodic table that could produce a spectrum with these five very, very distinct kinetic energies?

And so the way you think about this is you want to find what elements are going to have five different kinds of orbitals. And so we can list the first set here-- 1s, 2s, 2p, 3s, 3p, that's five. And then you need to know from the periodic table where are the elements where you're filling the 3p. And those are over here. So again, we talked and these problems aren't on the exam.

But on the exam, you need to know that this is 1s-- you're filling 1s, you're filling 2s, you're filling 2p, you're filling 3s, you're filling 3p-- that you need to interpret. You'll be given a periodic table. But you need to be able to know what orbitals are being filled in the different parts of the periodic table. So let's just try a practice with that.

All right. Let's just take 10 more seconds. All right. So we might need to work on the sort of counting.

So again, you want to think about you have 1s, 2s, 2p, 3s, 3p, 4s, 3d, and 4p. So I think if we get the counting down we'll be good. But again, you need to look at the periodic table and know what's getting filled.

All right. So let's move on and talk about electron affinity. And maybe we can squeeze in some electronegativity at the end. These are very related topics and pretty fast.

All right. So electron affinity-- the ability to gain electrons. So what we're talking about here is how likely atom X is to grab an electron and become X minus.

So we often think about halogens when we're talking about this like chlorine. So we have Cl plus an electron, Cl minus. And here the change in energy associated with gaining that electron is minus 349 kilojoules per mole. Energy is released. And that means that the ion is more stable than the parent.

So chloride is very happy to become Cl minus. And so you think about energy being released, if you think about a kid-- my husband's out of town, so I was watching our six-year-old daughter this weekend. And she was racing around like a crazy person until she collapsed in a heap.

So energy is released. And she became a more stable six-year-old. So that's what's happening with chloride as well-- more or less.

So here, the electron affinity is minus the change in energy. So if we talked about the electron affinity of chloride for the electron to become Cl minus, you would say that was plus 349 kilojoules per mole. So unlike ionization energy, which is always what? Positive or negative-- ionization energy? Always positive.

Electron affinity can be positive or negative. And that tells you something about how much it wants to gain electrons. So nitrogen plus an electron, going to N minus, has a positive energy

value here and has a negative electron affinity. So N minus-- the minus one ion is less stable than its parent. So it is not as happy as chloride to do this.

So trends in ionization. Usually you have an increase going across and a decrease going down. And let's just consider noble gases and what you think about them. So we'll do one final clicker question.

It should be pretty fast. OK, ten seconds. OK, yup. They are, in fact, negative.

And so we can think about this over here. Noble gases have negative electron affinities. Noble gases are very happy the way they are. If you had to add another electron to them, you would need to make a new subshell there, which they don't want to do.

And so halogens, on the other hand, which are right next door, have highest electron affinity. So if you're over here, they want to gain an electron and become a noble gas. Noble gases want to stay the way they are. So the increase trend ends right before you get to the noble gases. They're in their own category.

OK. So we're going to end with that. And we'll continue with electronegativity on Friday.