Chemistry: Challenges and Solutions

Unit 4: Organizing Atoms and Electrons

The Periodic Table

Hosted by Mala Radhakrishnan

[Tease]

JULIE GOSTIC: Basically, the periodic table is our lifeline.

KEN MOODY: As a chemist, I use the periodic table on a daily basis. All chemists would find useful information in the periodic table.

DANIEL ROSENBERG: And now we're going to react potassium with water.

SAM KEAN: The elements are the basic building blocks of the universe. And the periodic table orders them in a very clever way. But the periodic table, contrary to what you might believe isn't set in stone.

It is an extraordinary achievement that nearly 118 elements, either naturally occurring or synthesized, have been identified so far. Many elements have been known for millennia, but scientists continue to isolate new ones today.

JULIE GOSTIC: We are looking at the Periodic Table and we are saying, it should be right there. And then, actually, maybe it is, maybe it isn't. So it's a big guessing game until you actually produce it.

KEN MOODY: We're trying to fill in the blanks and we're also trying to find out how many more blanks there are.

[Title: Unit 4 – Organizing Atoms and Electrons]

[SEGMENT 1: Arranging the Elements]

MALA RADHAKRISHNAN: I'm Mala Radhakrishnan, a professor of chemistry at Wellesley College. I am interested in the periodic table of elements, just like I'm interested in music. Both music and chemistry rely upon patterns and rules to form universal languages. The periodic table of the elements is a fundamental tool that all chemists use. The genius of the periodic table is in its organization.

SAM KEAN: Now there are lots of other arrangements out there, and in fact there are some really ingenious arrangements. One that I really enjoy has hydrogen at the center and then there are other elements, spiraling around it like a galaxy. There are some that look kind of like board games, instead of being nice boxes they kind of wander around the board.

There are some that are in 3-D; one of them I saw has a nice double helix motif. There's pyramidal shaped ones, there's honeycomb shaped ones. It's really kind of spectacular. But they're not always the easiest when you're trying to learn the periodic table or to teach the periodic table.

MALA RADHAKRISHNAN: By 1869, a total of 63 naturally occurring elements had been discovered, just by exploring the environment. As the number of known elements grew, scientists recognized patterns in their chemical properties and began to develop classification schemes.

Chemists in the19th century were not aware of electrons or protons. Most of their information came from measurement of atomic masses and other observed physical and chemical properties. Dmitri Mendeleev is often considered the father of the periodic table.

The arrangement he eventually came up with was so successful that it has endured through the discovery of dozens more elements, as well as new ways of understanding atoms that Mendeleev and his contemporaries could never have imagined.

MALA RADHAKRISHNAN: Mendeleev arranged his periodic table according to the masses of the elements. There is a reason why his table is called a periodic table, and not just a chart of the elements. “Periodic” refers to patterns or cycles.

Each row of the table represents a pattern of chemical properties that repeats in the row beneath it. In a given column elements are all at the same point in that cycle, and therefore have similar chemical properties.

Let’s take a look at the fourth row or period. Starting with potassium, which has the largest atoms in its period, atoms generally get smaller as you move across a period. Also, elements show differing levels of reactivity across a period. While potassium is very reactive, at the other end of this period is krypton, a noble gas, the least reactive element in its period. In between, the reactivities are high or low depending on which column or group the element is in.

Next, in period five, the first element is rubidium. Rubidium is the most reactive element in its period. Again, as we move across, the atoms are trending smaller in size, and the reactivities go up and down, but in the same pattern as the period above.

In this way patterns repeat in each period, resulting in similar properties within each group. In our example, the first group contains highly reactive elements including potassium and rubidium.

The last group, the Noble gases contains generally unreactive elements, including krypton and xenon.

SAM KEAN: The next big breakthrough with the periodic table came right before World War I, in England, with a man named Henry Moseley. He found that the number of protons in the nucleus corresponded exactly with an element’s spot on the periodic table.

MALA RADHAKRISHNAN: Moseley arranged his periodic table according to atomic number. A few years later it was confirmed that this atomic number was based on the number of protons in each element. The atomic number, the number of an atom’s protons, is how we still order the elements. Each box contains information about the atoms of one element.

Typically you will see the one or two letter atomic symbol, its atomic number, and its average atomic mass. The atomic symbol for sodium, for example, is Na, and its atomic number, its number of protons, is 11.

When we arrange the table by atomic number, it generally coincides with Mendeleev's table, which was arranged before protons were even discovered. So this suggests a link between atomic structure and observed periodic properties such as reactivity.

Reactivity is the tendency of an element to undergo chemical reaction, either by itself or with other materials, such as the air around us.

[SEGMENT 2: DEMO - Periodic Trends in Reactivity]

DANIEL ROSENBERG: Today we are going to look at periodic trends in reactivity. The first column on the left starts off with hydrogen. But hydrogen is a gas at room temperature and pressure, and so we're not going to worry about it. Rubidium, cesium and francium are also in this column. Cesium and rubidium are dangerously reactive and francium has never existed in one place in more than a miniscule amount and it's intensely radioactive.

Potassium, sodium, and lithium are the three alkali metals that we're going to look at today. You can see how quickly they react with the oxygen or with any moisture in the air.

We're going to drop them one by one into water and see how they react. For this part of the experiment safety gear includes gloves, safety glasses, a lab jacket, a metal screen over the beaker, and a fume hood.

So the first metal that we're going to react is lithium. The lithium is reacting with water, pulling apart the water, taking the hydroxide for itself, making lithium hydroxide and leaving hydrogen to bubble away. The bubbles that you see frothing away from the lithium are all hydrogen gas – a relatively calm reaction.

So now I'm going to react sodium with water. Sodium is even more reactive. It generates hydrogen and sodium hydroxide and a lot of heat. Heat ignites the hydrogen gas to the point where it explodes. That was fun!

And now we're ready to react potassium with water. Potassium is more reactive still. It burst into flame the second it touches the water and it generates hydrogen and potassium hydroxide. It reacts so quickly the potassium metal never gets hot enough to explode. So, even though it's a more reactive metal it's a little less spectacular when it reacts with water.

So we've designed this experiment carefully to use small pieces of metal in a way that we get an expected result. The lower we go in the Alkali Metal group the more reactive the metal is. The lithium fizzes, the sodium explodes, and the potassium burns away before it has a chance to explode.

But what would happen if, instead of a pea-sized piece of sodium, we were to take a truckload of sodium and throw that into water. That would be interesting!

1947 NEWSREEL NARRATOR: 20,000 pounds of highly dangerous metallic sodium head for destruction in lake Lenore, Washington. A 3500-pound container of sodium hurdles into the lake and crashes through a foot of ice. As the water seeps in, smoke rises through a series of muffled explosions. The containers go up with spectacular results as water and sodium meet.

DANIEL ROSENBERG: This is not something to try at home.

[SEGMENT 3: Electron Configuration]

MALA RADHAKRISHNAN: Like many other trends on the periodic table, reactivity with water is directly related to how an atom's electrons are arranged. Elements in group one, the alkali metals, have similar chemical properties because they have similar electron configurations.

Now keep in mind that what I'm about to draw is just a model to help us understand this concept, and not what an atom really looks like. Electrons in an atom are grouped into so-called "shells." Each shell can describe a specific number of electrons before it is considered full. Any more electrons must go in additional shells, likely to be found increasingly far from the nucleus.

When an atom comes into contact with another chemical species, it is only the "outermost" shell–also known as the valence shell–that will be available to interact.

Sodium has 11 electrons - two in its "first" shell, eight in its second shell, and one in its outermost, or valence shell. Because this one electron is likely to be far from the nucleus and therefore feels little attraction to the atom, sodium tends to lose this one electron when it participates in reactions. Its new valence shell–the second shell–has eight electrons in it.

All the alkali metals–lithium, sodium, potassium, and so on, have only one electron in their valence shell. The only difference is which shell is the valence shell. Because all these atoms start out with only one electron in their valence shell, they will "look" similar to each other from the perspective of a reacting partner, and will therefore react similarly with such partners. A very important observed principle is that atoms tend to gain or to lose electrons in a way that leaves them with eight electrons in their valence shell.

SAM KEAN: The motivation of an atom is to get eight electrons in its outermost energy level. That's basically, to me, half of chemistry in one sentence. The atoms are going to beg, fight, borrow, make and break alliances, do whatever they have to do to get eight electrons in their outer energy level. That's really what they're always motivated by, what they're always striving to do.

MALA RADHAKRISHNAN: The periodic table is laid out in a way that helps us to understand how many electrons are in each shell of an atom.

Each row, or period, of the table contains elements with the same valence shell. For example, all elements in the third row have three shells of electrons, with the third shell being the valence shell. Elements in the same column or group of the table generally will have the same number of electrons in their valence shell, and will have similar chemical properties because of this.

Let’s take a look at the Group next to the Alkali Metals, the Alkaline Earth Metals. Because they’re in a different group, they have a different configuration of valence electrons. What might that tell us about the reactivity of the second group, when compared with the first?

[*SEGMENT 4: DEMO – Reactivities of Alkaline Earth Metals*]

DANIEL ROSENBERG: So, the second column of the periodic table starts with beryllium. But beryllium is a deadly poison and we’re not going to experiment with it today. We’re going to look at magnesium and calcium. Magnesium metal comes in ribbon form. And I’m going to add a curly cue of magnesium metal to water.

And there’s no reaction. Magnesium doesn’t react with cold water. But let’s see what happens when we give a little extra oomph to the water by heating it up to boiling. I’ve got another curly-cue of magnesium and I’m going to add it to the boiling water. All of a sudden we see fizzy bubbles coming from the magnesium ribbon. Magnesium metal, in boiling water is reacting to form hydrogen gas, which is bubbling away. And it generates magnesium hydroxide.

What can we expect from calcium, the next metal down in the alkaline earths? I’m going to drop calcium into cold water at first. And we can see right away, lots and lots of bubbles. That’s hydrogen gas being formed by the reaction of calcium with water. The other product is calcium hydroxide.

Magnesium only reacts with water when it’s boiling and calcium reacts with water at room temperature. And so we see that just like with the first column of the periodic table, with metals the lower we go in the periodic table the more reactive the metal is.

MALA RADHAKRISHNAN: The elements in the second group react in a similar fashion to those in the first group. But they aren’t quite as reactive. By adding energy in the form of heat we increased the magnesium’s reactivity. All chemical reactions are sped up by adding heat, and so now we can see the more slowly reacting magnesium fizzing in front of our eyes.

As we move further down group two, the elements don’t need as much heat energy to help them react with water, because, as in group one, elements get more reactive as we move down a group.

Beyond periods and groups, the table organizes elements into blocks. These are called the s-block, the p-block, the d-block, and the f-block. The blocks reveal more about how the electrons are arranged, where they are likely to be, and which electrons are the valence electrons. For the first three blocks, the s, p, and d blocks, the periodic patterns are relatively easy to understand, with a key aspect being that elements within a group share very similar chemical properties.

However, for the last block, the f block, periodicity no longer follows the same predictable pattern, and as more elements were recognized some changes in the table's layout seemed to become necessary.

[SEGMENT 5: Seaborg's Elements]

During the Second World War and then as the Cold War intensified, Berkeley, California became one of the world's hotbeds of nuclear chemistry. One of the most accomplished scientists of that time, Glenn Seaborg, worked at Lawrence Berkeley National Laboratory. A pioneering member of Seaborg's team was Darleane Hoffman. Her career has centered around the capture and chemical analysis of elements with very short lives, just minutes or even seconds.

DARLEANE HOFFMAN: One of the biggest advances in periodic tables was made in 1945 by Glenn T. Seaborg. After they'd finished developing the procedures and separations for plutonium during World War II, he thought they should go ahead and look for the next elements after plutonium.

Well, they couldn't find them because they had them placed in this series where americium should have acted like osmium. And plutonium should have acted like rhenium. Well, they didn't. So he said, "Well, maybe, maybe these things act like lanthanides or rare earths." The lanthanide series, which was already known, is up here. He came up with something called an actinide series where all of the actinides were put down here.

His friends and colleagues said: "You're crazy if you, it'll ruin your reputation if you put out anything so foolish as that." It turned out he was right and it actually made his reputation.

MALA RADHAKRISHNAN: So important was Seaborg's contribution in rearranging the periodic table that, in his lifetime, an element was named after him, element 106, Seaborgium.

SAM KEAN: Seaborg and his team, they were involved in creating element 93, 94, 95, 96, 97, on and on and on. They inked in box after box on the periodic table together and that whole team out there at Berkeley was really the greatest element-making machine the world has ever seen.

MALA RADHAKRISHNAN: Glenn Seaborg, like Mendeleev, left some blank spots in his layout of the periodic table. He placed an imagined row of elements under his actinides, which he called "Superactinides," beginning with element 122.

These elements have yet to be found in nature or synthesized in any laboratory, and scientists don't know how these so-called super-heavy elements will behave chemically. Will they form a mysterious g block, with different kinds of electron configurations?

We won't know the answer unless these super-heavy elements are isolated and analyzed.

[SEGMENT 6: Synthesizing New Elements]

JULIE GOSTIC: We need to turn it into a very uniform distribution…

MALA RADHAKRISHNAN: While most of the elements on the table were discovered in nature, nuclear chemists have synthesized nearly two-dozen additional elements. Now it may seem strange to "create" an element without knowing its properties in advance, but several such synthesized elements have eventually found a place in industry, medicine, or science.

JULIE GOSTIC: Way back when we discovered americium, we didn't know it was useful. But now it's being found in industrial standards from all over the world. There are little, tiny americium sources inside your smoke alarm.

KEN MOODY: Nuclear reactors use heavy elements as fuel. The californium that's produced at the high flux reactor at Oak Ridge, besides being a valuable research material, has very many practical applications in logging wells in oil exploration.

MALA RADHAKRISHNAN: But to start with new elements are pursued not for their practical uses, but to broaden scientific knowledge. We visited a team of scientists at Lawrence Livermore National Laboratory in California investigating super-heavy elements.

NAREK GHARIBYAN: The goal of our research group here at Lawrence Livermore National Laboratory is to participate in experiments in collaboration with groups in both in Germany and in Russia trying to produce elements at the edge of the periodic table.

JULIE GOSTIC: Usually when we talk about heavy elements we're talking about things above uranium. When we get into super-heavy elements, we're talking about the 107's through 117. That's really what we are interested in.

MALA RADHAKRISHNAN: These scientists use a multi-step process to synthesize heavy elements. First, they isolate and purify atoms of two elements they wish to use. Then they use an atomic accelerator to try to combine the nuclei of the two atoms.

In the event that the two nuclei do combine to form one large nucleus, scientists quickly run both physical and chemical tests to see if was the element that they were searching for.

KEN MOODY: The mathematics is relatively straightforward. If I want to make an element with 114 protons, I have to assemble it from reactants that have between them 114 protons. Less won't do; I have to have the 114.

So in our case, we take element 94, which is plutonium, and we irradiate it with calcium, which is element 20. 20 and 94 make 114.

NAREK GHARIBYAN: You need to follow certain procedures to produce these elements. One of the first steps is to obtain the material to prepare a target. In order to obtain this target material, it's purified or separated from a matrix that includes other elements. After separation and purification of the material, we can use the solution that contains the material to produce a target that will be used for super-heavy element production.

JULIE GOSTIC: This system actually takes the plutonium out of solution and puts it directly on this foil in a very thin layer. Plutonium atoms are going to interact with the beam that's hitting it. The calcium ion beam will come in; hit the atoms. And they form new atoms, these heavy elements that we are interested in.

EVGENY TERESHATOV: The second part is chemical part. We have to collect all the elements of interest and separate and isolate them from the other by-products. And carry out the experiment.

MALA RADHAKRISHNAN: The challenge in investigating new elements is not only in creating them. It is also in analyzing them quickly enough.

NAREK GHARIBYAN: These elements live for a very short time, seconds to milliseconds. The nucleus that is formed is transported through a magnetic field into a detector, where we can determine what element it is.

KEN MOODY: We can't plan on when that atom is made; it could be made any time during the day. We actually have to do chemistry every couple of seconds in order to be able to have any chance of seeing the atom that we produced.

EVGENY TERESHATOV: Usually we use ion exchange separation. So we use a column that looks like a tube with resin inside.

MALA RADHAKRISHNAN: The resin traps the elements of interest, separating them from unwanted materials. Designing an automated system involves investigating what resins will specifically bind to heavy elements. In some cases the goal is to trap a single atom of interest, to compare its behavior to that of similar elements on the periodic table and to infer its chemical properties.

NAREK GHARIBYAN: We typically initially do the work with homologues, which are elements that are either in the same group on the periodic table, or are believed to have similar chemical properties to the heavy elements that we want to study.

EVGENY TERESHATOV: So if I take those homologues and inject them into the system and create the chemical procedure and show that I can separate them, then I believe that my procedure works, and then I can go to the cyclotron, see that I have super-heavy elements, prepare the same solution and inject it to the same system.

KEN MOODY: So element 114 is below lead; so if we produced short-lived lead isotopes and develop a chemistry experiment, then we can deploy that to the Dubna Laboratory or to the German laboratory and perform a chemistry experiment based on what we develop here.

EVGENY TERESHATOV: We're interested in the micro amounts. We are looking for several atoms, maybe one atom, if we're lucky.

KEN MOODY: Now with automation techniques and other chemical techniques that we're developing, the possibility of doing 10,000 experiments in a day, one of which might have an element 114 atom is possible.

JULIE GOSTIC: It's very exciting to create new elements. All the sciences come together. You have engineering. You have chemistry. You have physics. You have mathematics. All of those things have to work to make this possible and there's a lot of people that are involved. So when it finally works, it's like, for a chemist, it's like landing on Mars.

KEN MOODY: The search for the end of the periodic table is not over. We have not reached the end of things. Right now we're working on elements 119 and element 120. But at element 123, chemists get very, very excited, because you get a whole new class of chemical compounds.

DARLEANE HOFFMAN: You don't know whether the periodic table is still going to be a good guide or not. But the way to find out, of course, is to try to produce these elements and then see.

JULIE GOSTIC: So these are the little plutonium atoms that are going to interact…

[WRAP-UP]

MALA RADHAKRISHNAN: It's amazing that scientists can synthesize new elements. Chemistry plays a crucial role in helping us understand elements in the world around us now as well as those still yet to be seen. We do not know what the future of heavy element research will be, and so the periodic table is a living document, ever-changing.

For now it is the best, concise document we have to help explain the myriad chemical and physical properties of the basic building blocks of our universe and the relationships between them.

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