Chemistry: Challenges and Solutions
Unit 3: Atoms and Light
Exploring Atomic and Electronic Structure
Hosted by Michael McCarthy

[Tease]

Light travels to us across galaxies and within our solar system.

KELLY KORRECK: We're seeing the sun in the extreme ultraviolet. Here, what you'll see is a solar flare.

Light interacts with matter at the subatomic level

WAYNE STRATTMAN: When we put electricity into gas we get different characteristic colors.

DANIEL ROSENBERG: Atoms emit very specific colors of light.

We can use light as an investigative tool.

MATTHEW BRENCKLE: We think that it was made by Paul Revere in 1798.

Even to probe the mysteries of our past.
To understand how light interacts with matter we have to understand the structure of atoms, and how their electrons behave.

[Title: Unit 3 – Atoms and Light]

MICHAEL MCCARTHY: Atoms are tiny. 100,000 atoms could fit across a human hair. This means that we cannot hope to observe them with the naked eye.

Hi, I'm Michael McCarthy and I'm an astrochemist studying the chemical composition of the universe. My work overlaps astronomy with chemistry.

Astrochemistry is the study of elements and molecules in the universe. We investigate how they interact with light and with each other. My research is related to the atomic and chemical composition, evolution, and fate of molecular gas clouds between stars. It is from these clouds that solar systems form.

It's important for me to understand the structure of atoms and molecules and the ways that they interact with light.Spectroscopy is the tool I use.

While we may think of light as something that shines or glows, light includes visible light as well as ultraviolet, infrared, radio, and X-rays. All of the forms of light together make up what we call the electromagnetic spectrum.

We can explore matter by looking at the light it absorbs under some conditions, or the light it emits in others.

[SEGMENT 1: Making Light with Electrons]

WAYNE STRATTMAN: I'm Wayne Strattman. The work I do as an artist relates to chemistry in that I'm mixing gases and various vapors together in various proportions and pressures and then exciting them, giving them energy. I'm specifically looking for visual effects. Kinetic effects.

By varying the pressure I can get a variety of different effects and motions. I can make it move like lightning, or I can just make it a soft subtle glow. When we put electricity into gas, depending on the gas that gives a characteristic single color to the gas. Neon – orange-red, and argon – that pastel-purple. And in the case of xenon gas you get the characteristic color of this purplish blue

Well, I always like to say in my business that we're trying to be masters of 19th century technology. Because that's where this all started.

[SEGMENT 2: Atomic Models]

In the late 1800s, with a new ability to effectively remove the air from glass tubes, creating a more effective vacuum, a new phenomenon was observed.

When an electric current was applied to the tube it appeared that something was being emitted from one end, hitting the other end.

It originated at the negative terminal, or cathode, and traveled to the positive end, or anode. Scientists called the phenomenon a cathode ray, and the devices that produced them, cathode ray tubes.

Scientists like the British physicist J.J. Thomson, performed experiments with cathode ray tubes to try to understand what the so-called cathode rays were.

[SEGMENT 3: DEMO – Cathode Ray Tubes]

WOLFGANG RUECKNER: What they found was that a magnetic field affects these cathode rays. For example bringing a south pole near this beam deflects it upward. And bringing a north pole, if I bring the magnet around towards the beam, deflects it downward. Likewise, if we apply an electric field to this, if I make this end positive and this end negative, if these are negatively charged particles they will get attracted to the positive plate inside here. Like this. And if I reverse the polarity, then they get deflected the other way, because now the bottom is positive.

So we can deflect these cathode rays with electric forces or magnetic forces, or both. In fact, we can balance those two forces. Have one undo what the other one does. And make the beam go straight. And that's what J.J. Thomson did. And was able then to figure out the ratio of charge of these cathode rays to their mass. And he found out the mass was exceedingly small. And the charge, we know, is the charge of an electron.

Thomson measured how much the cathode ray was deflected in both electric and magnetic fields of known strength. Using these measurements and the physics of the time, he was able to figure out the ratio of the charge on the electron to its mass. While Thomson was not able to measure the charge or mass of the electron, he laid the groundwork for future scientists to do so.

MICHAEL MCCARTHY: Cathode ray tubes have not been the subject of research for many years. But the technology is still very useful. Cathode ray tubes in fact have been used in televisions for nearly a century. In my laboratory we use oscilloscopes and spectrum analyzers, all of which use cathode rays to display and analyze electromagnetic signals, which are used in many of our experiments.

J.J. Thomson deduced from his experiments that there are different parts of an atom, with positive and negative charges. While he is credited with discovering electrons, Thomson didn't understand their arrangement within the atom.

His model, which he called the "Plum Pudding" model, didn't have a nucleus. In his model the positive charge filled the atom, and the negative charge came from points scattered evenly throughout – in his analogy, the plums.

MICHAEL MCCARTHY: It's important to understand that atomic models are more like analogies than perfect representations. Atoms are so different from things we know from our everyday experiences, that any physical representation is bound to have flaws. No model is perfect, but good models help us understand better the structure of atoms.

The next important step in understanding atomic structure came from the experimentation of chemist Ernest Rutherford, who developed the first nuclear model of atoms.

Rutherford's team fired alpha particles - positively charged particles emitted by a radioactive substance - at thin gold foil.

MICHAEL MCCARTHY: According to Thomson's "plum pudding model", the positive and negative charges were distributed evenly throughout the space inside the atom.

If this were accurate, all of the large, positively charged alpha particles should have easily passed through the foil. But Rutherford's results were unexpected.

[SEGMENT 4: DEMO – Rutherford's Experiment]

WOLFGANG RUECKNER: So what we have here is a model of Rutherford's scattering experiment.

So I'm going to send this puck, which is the α-particle in towards the nucleus. And these two magnets are going to repel each other. So in the real atom the forces are electrical forces. We're using magnetic forces as our way of doing the interaction. So let's give it a try.

So that was very little deflection. This is almost ninety degrees. And this is basically straight back. That's something that's absolutely impossible with the J. J. Thomson model.

So Rutherford's experiments showed that most of the alphas went straight through; a few were deflected a little bit; but there were a few of them that came straight back and that can only happen if you concentrate all of that positive charge into a central kernel, the nucleus. And that was a remarkable result.

MICHAEL MCCARTHY: From these results, Rutherford developed the first nuclear model of the atom.

He concluded that atoms have a very small positively charged region in the middle, where most of the mass is, which he called the nucleus.
A much larger region with very little mass containing negatively charged electrons, surrounds the nucleus.

In 1913, physicist Niels Bohr proposed a model of the atom using some of the new research about energy.

His model, often called the *Bohr Model*, showed electrons orbiting around a nucleus in distinct shells–a planetary model. More energized electrons orbited further from the nucleus in higher energy shells.

The most familiar image of the atom shows electrons circling around a nucleus.

But this image is a deceptive oversimplification because the electrons do not actually orbit the nucleus. More accurately the electrons can be anywhere in a specified region which is called an electron cloud.

MICHAEL MCCARTHY: On average the width of the nucleus is one hundred thousand times smaller than that of the entire atom. So, if the nucleus were the size of a golf ball, the whole atom would be the size of this football stadium, with the electron cloud extending all the way to the edge of this stadium.

The most accurate and sophisticated model to date is called the Quantum-Mechanical Model. The quantum-mechanical model still places electrons in different energy levels.

But in this model the positions of electrons are understood in terms of their probable locations.

MICHAEL MCCARTHY: The quantum-mechanical model can be unwieldy and hard to visualize, so chemists and teachers still often use the Bohr model.

Although it's less sophisticated, the Bohr model clearly depicts certain important atomic characteristics, especially those relating to energy. For example, we can use the Bohr model to explain how electron transition relates to the colors we see.

[SEGMENT 5: DEMO - The Flame Test]

DANIEL ROSENBERG: So! We're here to throw electrons up and watch them come crashing down. And I've got a selection of metal salts in water solutions. And we're going to look at how those salts react to flame.

And the reason that we're using flame is because the flame is going to bump up those electrons thermally. It's going to kick them into higher energy orbitals, and they're going to come back down. And when they come crashing down they emit light. And they emit light of a very particular frequency.

And so we're going to start off with lithium, on a tiny piece of wire. Shows bright red. Beautiful red color. So each one of those lithium atoms emits that red color.

So what happens with sodium? Sodium chloride, table salt, has an intense yellow color. Lots and lots of yellow light. So now, what about calcium? So calcium has this beautiful orange color, rich orange color. And staying with the periodic table theme, we're going to go down from calcium to strontium. Strontium is a metal that's used in fireworks to get this red color. Beautiful strong orange-red color.

If we want an intense green – and that's what we do for fireworks – we go with copper. And copper is the metal used for greens and blues. So we get these wonderful, wonderful colors out of copper. So these are the colors that the flames turn when we kick those electrons up in energy level, and let them fall.

[SEGMENT 6: Observing Sunlight]

MICHAEL MCCARTHY: Each element interacts with light in a specific way. By using different techniques and comparing data, scientists identify elements based on unique spectra. This is called spectroscopy. Chemists and astrophysicists use spectroscopy to determine the chemical composition of stars.

KELLY KORRECK: My name is Kelly Korreck, and I'm an astrophysicist at the Harvard-Smithsonian Center for Astrophysics.

I was actually very intrigued by stars and observing when I was very young. And solar physics happened almost by accident. I was studying shock waves in supernovas and found out there are similar processes in the sun but there's a lot more data.

My research has, probably, two main parts. The first is analyzing data, such as that behind me, from the sun, in extreme ultraviolet and X-rays. So this is very high-energy events, such as solar flares, or coronal mass ejections, where billions of tons of material are released from the sun, and understanding the processes that actually cause these eruptions. And the second part is actually building instruments, such as those that take the images behind me

So the image wasn't taken from a terrestrial telescope. The earth's atmosphere actually protects us from parts of the electromagnetic spectrum that could possible damage us, such as the EUV and X-rays.

However, the very interesting astronomy processes that I study happen in the EUV and X-rays. So this telescope is actually flown on a satellite in order to get above the earth's atmosphere and take these pictures.

MICHAEL MCCARTHY: Astrophysicists use light to study the universe, because the environments that we wish to study are far away and inhospitable for people or instruments, such as the surface of the sun.

KELLY KORRECK: So you might be wondering why these images are in black and white. They aren't recorded on traditional film in terms of color. But what we then do is, we then false-color them using the computer, in order to distinguish differences between the different wavelengths

In order to look at this as scientists do, we're now going to put these images into color.

The electromagnetic spectrum is important in my work because it allows me to tell what elements are actually present in the objects I study. This is relating to the wavelength of the light.

Wavelength is a measurement of distance; it's the distance between the peak in oscillation of the light. And that measurement can range from things the size of a football field, to the X-rays, which are the size of an atom. And Light that we traditionally see as humans is just a very small portion of that electromagnetic spectrum called the visible light. And the X-rays are the wavelength that I do most of my work in that is around one ångström. And an ångström is a very small measurement. It's 10^{-10} meters. And that's one ten billionth of a meter.

Light is described as having wave-particle duality. That is, it behaves both as a wave, like a ripple on a pond or the sound of a vibrating string. And as a stream of particles, individual packages of energy called photons.

Whatever term we use, we are describing the same phenomenon. During an electron transition, energy is released when electrons drop down to a lower energy state. If the energy is released as light, we can think of it as wave-like electromagnetic radiation, or particle-like photons.

KELLY KORRECK: There is a specific energy associated with each transition for each element. And this helps me with my work in terms of the fact that it lets me determine which element I am actually looking at based on the wavelength of light. So once we understand the photon that's coming out we can trace it back to the different element.

What we're seeing here are four images of the sun. This is the sun in the extreme ultraviolet: the 171 angstroms. Others that you see over here are the 304 angstroms. We have the 193. And the bottom is in 211 angstroms.
Now brightness is also important. The areas where there is more brightness means that there are more photons coming from that element in that region so that gives me a good diagnostic of things such as density of the region.

Now the scientists had a lot of discussion as well as arguments over which color to choose for which wavelength, because it's just a representation, it's not the actual color that you see coming into the CCD.

So we chose these colors mainly because the eye is most effective in seeing in the yellow-green. And this is an image that shows us a lot of detail. So you can pick out those details best when it's in a color range that the human eye is optimized for.

So for instance, you see these beautiful loops whereas if you go over here to the 304 angstroms for helium, you don't see those loops.

So by putting all these images together at all these different wavelengths, we're able to tell the whole story of what's going on, on the sun.

The spectroscope is a tool originally used by Sir Isaac Newton. In 1666 Newton used a prism to split sunlight into its many colors. His experiments established that most light we see is made up of many different wavelengths or colors.

He introduced the term "spectrum" to describe the array of colors that make up visible light. This was the first step toward using light as a tool for exploring the atom.

[SEGMENT 7: DEMO – Emission Spectra]

DANIEL ROSENBERG: You might be wondering what that is. That's our diffraction grating. And we're going to put it in front of the camera so that we can see the various lines that come from the metal salts.

The spectral colors that you see are coming from all of the other lights in the room, so in order to see the light of just the flame we're going to have to turn off these other lights. So *[double clap, and lights go off]*

Sodium. Calcium. The diffraction grating acts to break up the different colors of the flame. And if those colors are coming in individual lines, then we see separate flames in each of those different colors. So even though the flame looks orange, when we analyze it there's a lot of green in there.

Strontium. Barium. Yeah. That's barium. And copper. These colors are characteristic of the elements. And so looking through a diffraction grating, that's how we tell elements apart.

MICHAEL MCCARTHY: When we perform flame tests on elements like sodium, calcium, strontium, barium, and copper, the spectra we see are predictable. We are using relatively pure samples, and we already know what colors they will produce. But what if we do not know which elements are in our sample? And what if there are multiple elements within the sample?

Engineers and application scientists at Olympus NDT have developed a sophisticated light-based device that can analyze samples for their chemical content.

[SEGMENT 8: Forensic Spectroscopy]

MEGAN ROPPOLO*:* So I'm here at the U.S.S. Constitution Museum because they have a small cannon, a howitzer, and they're very curious about what is the composition of the metal that makes up the cannon.

MATTHEW BRENCKLE: Old Ironsides, the U.S.S. Constitution, is right outside our windows here, the oldest commissioned warship afloat in the world.

Well we have this piece here from our collection. We think that it was made by Paul Revere in 1798. And we'd really like to know more about it, especially what it's made out of.

MEGAN ROPPOLO: So here I have our hand-held X-ray fluorescence instrument and I'm going to do a test. So within a couple seconds we can already see that it's about 82% copper, 11% tin, 6% lead, and a little bit of iron: so, basically brass.

MEGAN ROPPOLO: I think the easiest way to define X-ray fluorescence is, "X-rays in, X-rays out." X-rays fall on the high-energy side of the electromagnetic spectrum above UV light. So when the beam comes out of the nose, it hits the atoms in a sample. And it knocks out some of the electrons that are very close to the nucleus. So that makes an unstable situation for the atom. And so the outer electrons will then collapse in and fall down into those lower orbitals.
Since that energy has to go somewhere, it leaves the atom as what we call a secondary X-ray. And we can collect those secondary X-rays in a detector that's just behind this window here.

So when we test things like alloys we identify the elements and they sort of form a fingerprint, a little bit like the DNA of a person. Every alloy is different because an alloy is just a mixture of different elements in a metal.

MATTHEW BRENCKLE: I like that you're bombarding a cannon with X-rays. It's very fitting!

MEGAN ROPPOLO: Yeah, it does.

MATTHEW BRENCKLE: Paul Revere did a lot of casting in brass. Not only small cannons, but bells. And it just so happens that in 1962, one of his bells unfortunately was struck by lightning, but luckily for us, they sent a piece of that for analysis and it turns out that it was about 77% copper and 21% tin. So that's interesting, that the composition of these two pieces would be much different.

MEGAN ROPPOLO*:* There are several reasons why the two analyses could be different. The first one is that the bell, sounds like it was broken apart, so the people who tested it had access to the brass inside that had never been exposed to the atmosphere or to polishing.

Those are two things that can change the surface of a piece of metal, whereas this cannon has been around for a long time, exposed to the atmosphere and to polishing. With this technique, I only have access to the surface; however, the benefit is that I don’t have to break apart the cannon, which I imagine you wouldn’t like.

MATTHEW BRENCKLE: No, no, our curator would frown on that, I’m sure.

MEGAN ROPPOLO: Today, when we tested the cannon, I took the information that we got on the instrument and downloaded it onto my laptop to make it a little bit easier to see.

You’ll see here that these are the elements that we were able to detect. So here on the spectrum you’ll see several peaks. Each of these peaks is related to one of the elements that we detected. In this case, these two larger peaks are copper. The reason there are two peaks is because there are multiple transitions happening.

So you can see here on this spectrum, the x-axis is the energy of the X-rays. We use the units of kilo-electron volts. So in this technique, we talk about the energy of X-rays, although you can also relate that to the wavelength of the X-ray.

So here on the y-axis, we have intensity. So the intensity measures how many X-rays we’re getting to the detector of a particular energy. So you can see this example that the large copper peak has the most intensity and also has the highest concentration of about 82%.

Essentially, I think we were able to help the museum. We were able to confirm that the cannon was in fact made of brass, and to give them a recipe for what type of elements were in that brass. This type of information can be useful to historians. So maybe they will be able to take this information, compare it to other pieces, and confirm whether or not this cannon was in fact forged by Paul Revere, or maybe somebody else.

[WRAP-UP]

MICHAEL McCARTHY: Using electromagnetic energy as a probe, scientists continue to find innovative ways to explore the inner structure of the atom and the materials made out of these atoms.

In the century since electrons were first discovered, chemists have used the properties of electrons to study the structure of our world, and worlds far away.

Today, scientists are using the powerful connection between light and electrons to explore molecules and atoms across our galaxy. With a knowledge of atomic and electronic structure, chemists can understand the properties and patterns of the elements that comprise our world.

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