Atoms, Molecules, and Ions

Early Atomic Theory

Discovering Electrons Page [1 of 2]

The year is 1906. About 10 years earlier, J. J. Thompson had done the experiment, which gave us the charge to mass ratio on an electron. And now, a person named Robert Millikan was poised to do an experiment that would give us either one or the other; either the charge, which allows us to determine the mass, or mass, which allows us to determine the charge. And a very clever experiment that he performed was to determine the charge on an electron. And the experiment that he did has come to be known as the Millikan oil drop experiment, and you might even get to do this in your physics lab when you take physics.

The idea is that he took a box and into the box he sprayed some drops of oil, using something like this. Using something like an atomizer, he could spray drops of oil, which obviously are not to scale here, that flowed around in the space up above this black bar. Now, every now and then, if there's a hole in this black bar, one of these drops of oil is going to drop down, because of gravity. Most of them are just going to be smacking against the plate, but some of them are going to fall right through that hole. And what that's going to do is create a stream of particles that are falling pretty much in a straight line, pretty much in the same place. Now, suppose that we can see, we have a microscope or something that allows us to see these particles falling. That's going to allow us to know exactly where they are. Remember, these things are macroscopic. They're really big, so we can actually watch an individual drop as it falls through the hole.

Now, why is it falling? The reason why it's falling is because of gravity. Gravity is making these drops fall in a straight line through the hole. And there's nothing to keep the drop from falling. But suppose now that these black bars actually represent electrical plates. They're just parallel plates, two which we can apply a voltage. And that voltage we're going to apply such that the top plate is positive and the bottom plate is negative. Well, if the drops are neutral, if there's no charge on them, then still, nothing is going to keep the drop from falling. It's only going to fall as the result of the force of gravity. But suppose that we could ionize the gas in this region. We have an x-ray source that pumps x-rays into the space. It ionizes some of the air and the air splits up into ions and electrons, and some of those electrons that have been removed from the air get attached to the oil droplets. That's going to make the oil droplets ever so slightly negative. And being ever so slightly negative, they are going to be repelled by the negative plate at the bottom, and so there's going to be an upward force, or alternatively, they're going to be accelerated by the potential here. And so there's going to be an upward force on the drop. So now, there are two forces on the drop; there is the gravitational force that's down, and then there's the Coulomb force, which is up. And suppose we can dial in the voltage. We can dial in then the force that's on this drop, and we can dial it is such that there's exactly the same amount of force up as down. Well, when you have two forces that are exactly the same and they're in exactly opposite directions, then the particle doesn't move anymore. And that's exactly what happens.

So when the particle is not moving, what we have done is we have exactly balance the coulomb force, so the force that's up as a result of the electric field, and then the force that's down as a result of gravity. Well, we can substitute in an equation for what the coulomb force should be, or is, and what the gravitational force is, and that's shown here. We have $m \times g$, this is the mass of an oil droplet, a particular drop, times the gravitational constant, which is equal to the charge on that drop, times the voltage, divided by the distance between the plates. So it turns out that the separation between the plates makes a difference, as well. Now, we can solve this for q, the charge on a particular oil drop, and it's equal to the mass of a particular oil drop times the gravitational constant, which we know, times the distance between the plates, which we know, divided by the voltage, which we know. Remember, we can adjust this, we can dial it in. Now, we don't know what the charge is on a particular drop and what we have to do is adjust the voltage so that everything is balanced. And then what we do is we have an equation that relates q to these numbers. Well, the one that's difficult to measure is actually m, but let's, for now, say that we can determine what the mass of the drop is. Remember, this is not as difficult as determining the mass of an electron, because this is a macroscopic drop. And it turns out there, there is a way, by turning off the electric field and watching the velocity of the drop when it reaches terminal velocity. It's sort of however fast it can go and it doesn't go any faster, in exactly the same way a skydiver jumps out of an airplane and, at some point, he doesn't go any faster, because there's air resistance that's impeding his motion, and then there's the gravitational force. And so it turns out that there's a relationship between the mass and the terminal velocity, or how fast the drop falls in the absence of the electric field. Anyway, given that, you can determine what m is, and we know all these constants. We can calculate what the charge is on a particular drop.

And it turns out that we want to do this for a bunch of different drops. So I'll do a few, and then I'll get my students to do them, and they'll get other students. And suppose we do this for two, three, four, five weeks, and we just measure individual drops. So we focus on an individual drop and we balance this voltage such that the drop doesn't move, and then we determine what the mass of that particular drop is. What we're going to get is a bunch of q's, a bunch of charge on a particular drop. And it turns out that there isn't a continuum. In other words, the q can't take any value whatsoever. It only takes certain quantized sizes, charges, and those are given by this picture. So this is just, say, the first ten or twenty experiments. And what we find is that the charge that is on a drop occurs not in some continuum, but this big, or this big, or this big, or this big, or this big. And what we're going to do is we're going to take the greatest common divisor and assume that that represents the charge on one electron. So, in other words, this particular oil drop had one extra electron on it, but this one had three extra electrons on it. And this one had two extra electrons on it. And this one had four extra electrons on it. And so this amount, from here to the smallest step, that's what we're going to assume is the charge on just one electron.

So now, what the number that Millikan got was 1.59×10^{-19} coulombs. And it turns out that the sort of currently accepted value is 1.60×10^{-19} coulombs, where this is to three significant figures, and, in fact, it's known to probably something like eight or nine significant figures. As you might imagine, this quantity is a very fundamental quantity. What is the charge on a single electron? And then going back to Thompson, Thompson's value of charge to mass is 1.76×10^{11} coulombs per kilogram, and so that allows us to calculate, by taking the charge and dividing by the charge to mass, we can get the mass of an electron as 9.09×10^{-31} kilograms. Well, again, these numbers, both the charge and the charge to mass, are known to six or seven significant figures, and so the true value or the accepted value of the mass of an electron is 9.11×10^{-31} kilograms. But this just reflects the fact that there are some rounding errors and things like that when we go to only three significant figures.

The bottom line is that Millikan's very clever experiment, and it is now called "The Millikan Oil Drop Experiment," allowed him to determine what the charge was on an electron. And from that, we were able to determine what the mass of an electron is. Very fundamental quantities, because remember, at this time, those were thought to be the smallest pieces of matter that there could be in the universe.