

Atoms, Molecules, and Ions

Early Atomic Theory

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An interesting curiosity at the beginning of the 20th Century was radiation or, in particular, radioactivity. Now, basically what this is, is that there were certain heavy elements that were discovered that had an interesting property, that even though they were wrapped up in a bottle or protected, somehow enclosed, that they would emit some type of a mysterious radiation that was very different than light, in that it could pass through material. It could pass through black paper, for instance, and expose photographic film, even though the film was covered up. So again, this mysterious radiation was analyzed much in the same way that everything was analyzed back at the beginning of the 20th Century, that if you could generate a beam of the stuff, then you could pass it through an electric field, and watch how it bends, and get information about how heavy it was or what kind of material it was, what its charge was and so on. And so, in particular, Beckrell's and the Curies took uranium, or polonium or radium, which they had just recently discovered, and generated a beam of radiation. Now, this is simply by passing this radiation through a pair of slits, so that you get a well-defined direction or trajectory of this radiation, and then passing that beam through a pair of electric plates. So, once again, same idea as the Thompson tube, that we apply an electric field and cause this beam to deflect, if it's indeed charged.

Well, there were three things that came out of this radiation: gamma particles, which turned out not to be deflected at all by the electric field, and gamma particles turn out not to be particles at all, but rather electromagnetic radiation. We'll say a little more on that later; alpha particles, which were deflected by the magnetic field in such a way that it indicated that it had a positive charge, and beta particles, which were deflected in the opposite direction of alpha particles, and, in fact, were deflected to a much, much greater extent. So, once again, they either had a much higher charge and opposite to an alpha particle, or they were just a whole lot lighter than an alpha particle. Well, beta particle turns out to be just a very high-speed electron, so nothing unusual about it. But the alpha particles, now those were interesting beasts.

These were very high energy, very high kinetic energy, fast moving, in other words, particles that were sent out not by accelerating them, but they were emitted at high energies. They were quite massive compared to an electron. And this seemed like a wonderful opportunity, much in the way my son, when he wants to figure out how one of his toys works, the best way is to take it apart or smash it with a hammer and find out what's inside. And it's been very hard to break him of that habit. But he's got the scientific mind, because that's exactly what these guys did. They aimed these alpha particles at everything that moved and things that didn't move, trying to break them into pieces to find out what was inside.

So one of the big questions of the time was what did an atom look like? Were all the protons smeared out uniformly, or did they come in little clusters, or what exactly did the atom actually look like inside? We knew it had protons, we knew it had electrons. Some even speculated that there were neutral particles in the atom somewhere. Where were these things?

So an experiment was devised by Rutherford, actually not Rutherford, but his students, Geiger and Martson, but they were in his lab, and basically what they did was took this alpha particle source and shot it at a piece of gold foil. Now, the idea, again, was not to shoot, well, the idea was that in that gold foil were gold atoms, and that you could probe the structure within a gold atom and find out where protons and these mysterious neutral particles, if they were there, where these things were by looking at how that alpha beam was scattered off of the atoms. So the basic idea would be, to give you analogy, if I have a flashlight and I look at my hand. Suppose I hold the flashlight here and I project it past my hand and I look at the shadow of my hand on the wall. Even without looking at my hand, by looking at the shadow, I can see what my hand looked like, even if I can't see my hand, by shining this beam of light on it. And the idea is basically the same, that by looking at where the scattering was, where these alpha particles landed on this detector screen, you could infer what was inside the gold atoms, the hope was.

Well, what they found was absolutely astonishing. Most of the alpha particles, the vast majority went right through the gold foil as if it wasn't even there. Very, very strange. No scattering whatsoever. But, once in a while, an alpha particle would apparently bounce off of the gold foil and sometimes, so giving you a completely different trajectory, sometimes so radically different that it would be bouncing back towards the direction that it was coming from. Now, to paraphrase Rutherford, it was as if you were shooting a gun at a tissue paper and the bullet would bounce right off the tissue paper and come back at you. It was that astonishing. The only way that this possibly could happen is if all of the mass of the gold atom was isolated in one very, very small volume at the center, let's say, of the atom, at the nucleus of the atom. This was the term coined.

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And now, how small would that volume actually have to be? Well, a few calculations revealed that the volume or I should say the diameter of the nucleus would have to be about 10^{15} meters. Now, that's really, really small, but just how small is that? Well, the size of an atom, which we assume is very small, is 10^{-10} meters about. So five orders of magnitude difference. To give you an analogy again, if you were to take an orange and put it at the pitcher's mound at the Houston Astrodome, if the Astrodome was the size of an atom, that orange would be the size of the nucleus. So you can see a very, very small amount of volume, indeed, and nobody, nobody would have ever guessed that ahead of time. So this is an example of an experiment, which radically changed our ideas of what made up the atom.

But once we knew that that mass was located at the center, this gave us our more modern picture of what the atom looks like, the so-called plumb pudding model, which Thompson had put forth after doing his Thompson tube experiments and so forth, in which protons and electrons were uniformly scattered throughout the atom. That was abandoned right after this experiment began, because the experiment certainly would not support this type of model. Instead, the model that came into being was the so-called planetary model, where electrons were in orbit around a nucleus, again, a very small nucleus as far as volume, where all the mass, or the majority certainly of the mass was in the atom. And, of course, the analogy is obvious that this was such an appealing analogy, because it was like planets in order around the sun in the Solar System.

Now, the only problem with this model, as we'll find out, is it turns out that the electrons are not in orbit, but we have to have a very different understanding of what those electrons are doing. Nonetheless, as far as the locations of the electrons, they're occupying a volume much, much more massive than the volume of the nucleus. That certainly is true. And so, again, that's this fundamental paradigm shift that was brought about by the Rutherford experiment.

Now, there was still one missing piece. We knew about protons. We knew about electrons. We knew that there was mass not accounted for by the protons in the nucleus, in atoms. And indeed many had postulated the existence of a neutral particle having about the same mass as a proton, but there was no direct evidence for these so-called neutrons, because - remember how we measure, or again at the time, how people measured particles was they'd accelerate them in an electric field, watch them bend and figure out how big they had to be. And the problem was neutrons had no charge. So what are you going to do? You can't see the darn things. You can't accelerate them and bend them anywhere. So it took another twenty years beyond the Rutherford experiment before Chadwick devised an experiment that ultimately found the first direct existence of neutrons.

Now, the idea was to take these, again, these wonderful alpha particles, these miniature sledgehammers, and direct them into a film of beryllium. Now, by the way, there's no way that he had the foresight to know beryllium would be the magic thing that would give rise to neutrons. But you've got to understand that, at the time, people were aiming alpha particles at everything they could find, and beryllium just happened to be the material or one of the materials that would give rise to these neutrons. The neutrons couldn't be detected, but what you could do was scatter nitrogen atoms or other atoms, in this case the experiment was done with nitrogen, much in the way a billiard ball bounces off another billiard ball. The neutrons were being emitted out of the beryllium. They were being kicked out by the alpha particles, and those neutrons would bounce off nitrogen atoms. In the process of the collision, the nitrogen would be ionized. It would lose an electron, and so then you'd have a charged particle that would be flying off. And by looking at how fast that nitrogen was traveling, you could figure out something about this neutron being massive, and also being neutron in that you couldn't detect the neutron directly. And so, this was again the direct observation, the first direct observation of the existence of neutrons. And then by just accepting that, okay, neutrons do exist, we do have these neutral particles then, you could figure out what the mass of the neutron was by knowing mass of the proton and knowing the mass of an entire atom that would contain both the protons, and the neutrons and the electrons. So the neutrons, again, was that missing mass.

So that pretty much completed our picture, our more modern understanding of what an atom is, which is, once again, protons and neutrons clustered very tightly together in a very small volume at the center of the atom, at the nucleus, with electrons occupying a volume around it, a much, much larger volume again than the volume of a nucleus. And again, it's so appealing to think of these electrons in orbit somehow around that nucleus, and we'll find out that that's not quite right, but at least it's a starting part for us.

So finally, let's return, once again, to Dalton. We find that Dalton, although he didn't get it completely right, was pretty close to the right idea. All matter is composed of indivisible atoms - that's true as long as we're in the realm of chemical reactions, that the atoms are, in fact, maintained. But we do know that atoms, in fact, can be divided. They

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can be divided into protons and neutrons, and that becomes the realm of nuclear reactions then, when we're talking about that.

Element is a type of matter composed of one type of atom with characteristic mass. That turns out not to be right, because you can change the number of neutrons without affecting its overall charge at the nucleus. We'll talk much more about that soon. But it is true a compound is composed of atoms of different types. Chemical reactions involve rearranging those atoms of different types. And so, Dalton again, although he didn't have it perfectly, really did an enormous amount, a huge contribution into helping change the way we think about our microscopic world.