THE ELECTRON - Curated Transcript of BBC In Our Time podcast
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In Our Time is hosted by Melvyn Bragg. Melvyn's guests on this podcast are:

Victoria Martin
Professor of Collider Physics at the University of Edinburgh

Harry Cliff
Research Fellow in Particle Physics at the University of Cambridge

And

Frank Close
Professor Emeritus of Theoretical Physics and Fellow Emeritus at Exeter College at the University of Oxford

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Transcript:

[Melvyn Bragg] Hello. It was in 1897 that JJ Thompson discovered the electron and revealed that atoms, supposedly the smallest things, were made of even smaller things. Thompson's vision of atoms had these electrons scattered inside a ball like sultanas in a Christmas pudding. And over the last 125 years, our knowledge of them has grown from that exponentially. We can use electrons to reveal the secrets of other particles and why electricity exists. Whether we understand electrons or not, the applications of electricity and electrons grow as our knowledge grows. Yet many questions remain unanswered. With me to discuss the electron are Victoria Martin Professor of Collider Physics at the University of Edinburgh Harry Cliff Research Fellow in Particle Physics at the University of Cambridge and Frank Close Professor

Emeritus of Theoretical Physics and Fellow Emeritus at Exeter College at the University of Oxford.

[Melvyn Bragg] Frank, it's impossible to overstate the significance of electrons, but could you give us an idea?

[Frank Close] Well, electrons are constituents of atoms, and perhaps the most important property is that they carry electric charge. And when you charge your laptop or your phone or maybe even your electric car, you're storing up electrons to make use of. And electric current is just electrons on the move, and they flow through computer chips, through your nervous system and basically power all electrical industry. So a huge amount of modern technology is really electrons on the move.

[Melvyn Bragg] When you say huge amount, can you develop that a bit?

[Frank Close] I would almost turn it around and say, are there any things where electrons and electricity is not involved at some point. At this very moment, the fact that people are listening to us is because electrons within the technology here are on the move and sending signals out and making other electrons move around in their receivers.

[Melvyn Bragg] I mentioned J.J. Thompson [and we] will get into him in a moment. Can you tell us something about the context in which he was working and, in a sense, why it took so long to discover electrons? We just talked about the end of the 19th century, and now you tell us they invade and motivate almost everything...

[Frank Close] I suppose, electrical phenomena ultimately are buried deep inside atoms. So unless you get to know what's going on inside atoms, it's hard to extract the awareness of electrons. But electricity and magnetism, of course, have been known for thousands of years. By the 18th century, I guess, the idea of electrical charge, if you rubbed pieces of glass, you could electrify them and they would pick up pieces of paper and so forth by this strange electrical force. By the 18th century, lightning bolts coming from thunder clouds were known to be electrical phenomena, but nobody knew what the electricity actually consisted of. Right through the 19th century, you've got Faraday at the Royal Institution discovering huge amounts about electricity and magnetism. Then you get James Clark Maxwell encoding all of this information in equations, which have the remarkable result that electric and magnetic fields can propagate at the speed of light, which tells us that electromagnetic waves and light are the same thing. But all of these are phenomena. Nobody knows yet what causes them. Now, they knew that currents can flow through wires, and so the idea of maybe if you could remove the wires, you might be able to see the currents in the raw. And the way of removing the wires was to send electric current through gases. And as vacuum pumps got better, they could remove more and more of the air. And by the end of the 19th century, it became possible to actually send electric current through a vacuum. And it was in the course of looking at how electric currents pass through a vacuum that Thompson is credited with the discovery of the carriers of that current, namely the electron. And that was 1897.

[Melvyn Bragg] Thank you. Harry Cliff, can you talk about the laboratory in Cambridge where he worked and what was the context of that?

[Harry Cliff] J.J. Thompson: At the end of the 19th century, he's the Cavendish Professor. So he's head of the Cavendish Laboratory in Cambridge, which is an experimental physics lab in the city. And he's actually a bit of a strange choice to be head of the laboratory because he's actually a mathematical physicist - so more of a theorist, really, and also famously clumsy and Frank's, talking about these very delicate glass tubes that Thompson is using in his experiments. Thompson didn't build the experiments. The person actually built them was this glass blower called Ebenezer Everett, whom Thompson worked with, who's regarded as being the best glass blower in England by people in Cambridge, at least. So Everett spends days hand-blowing these really intricate tubes, bleeding in electrical wires so that you can pass this electric current through. And he very rarely lets Thompson anywhere near them because he's terrified that he will smash them. So you kind of imagine this scene of them doing the experiments where Thompson is sort of in one corner shouting orders at Everett, who is actually doing most of the manipulation. The question Thompson is really trying to answer... as Frank says, you have these glass tubes. You evacuate the air, you pass an electric current through and what had been observed is you get this green glow at one end of the tube, at the positive end of the tube, and there's a big debate about what's causing this green glow. And there are basically two schools of thought. Continental scientists tend to think there is some kind of electromagnetic radiation passing through the tube - so something a bit like light or radio waves - whereas Thompson tends to think that these are electrically charged particles and the experiments he does in Cambridge are trying to essentially prove that these things are indeed particulate.

[Melvyn Bragg] Can you give listeners any idea what these experiments were like? Or is that too far away from general knowledge?

[6:33]
[Harry Cliff] ...If you want to picture a scene you can imagine a darkened lab. So you have this glass tube that looks like a very elongated sort of light bulb, like an old filament bulb. It has a couple of electrodes that kind-of come in from the sides through wires and that would be connected to a power source. And at the far end of the tube there is a little luminous needle that can be adjusted; there's a little scale; imagine a bulb at the end with a scale on it. And basically the process is what Thompson is trying to do is he applies electric and magnetic fields to these particles as they pass through the tube and he finds that he can manipulate the position of this green spot by altering the magnetic field or altering the electric field. And essentially by balancing these two forces against each other he can measure the ratio of the electric charge of these particles to their mass.

[Melvyn Bragg] Why is that so significant?

[Harry Cliff] Well, the debate is really well, first the first point is if you can show that they're carrying electric charge and there's a relationship to mass that indicates that they are particulate. But the other thing that Thompson believes is that when he measures the ratio of the electric charge to the mass of these particles he finds that the mass is about 2000 times smaller than the lightest known atom at the time, which is hydrogen. And this indicates to Thompson that what he's actually discovered are subatomic particles, things that make up atoms. And he makes this claim actually at the Royal Institution in 1897 after he's completed his first set of experiments. And then he goes on to say "I believe these are the constituents of atoms" and that the audience will not accept; actually, one physicist claimed he thought Thompson was pulling their legs! So he has to then go away and do more experiments to try and build a case to really show that they are components of atoms.

[Melvyn Bragg] He described atoms as a plum pudding with electrons inside. Was it Rutherford? Who was Rutherford who tested this pudding?

[Harry Cliff] Yes, actually Rutherford is a PhD student at the time that Thompson is doing his pioneering experiments in the late 1890s. And then he then goes off and makes his name as a pioneer of nuclear physics in the first decade of the 20th century, comes back to the UK and he becomes the head of the lab at Manchester. And he does a very famous experiment where he essentially uses radioactive atoms to fire what are called alpha particles -
so these are particles emitted in a radioactive decay - he fires them at atoms of gold. And what he finds is very surprising. You can think of these alpha particles as like high velocity bullets. So they're incredibly fast moving, very energetic. Now, Thompson's big wobbly sponge-like atom; these particles should just go straight through it.... It's like firing a bullet at a sponge cake. You'd expect the bullet just to pass straight through. But what Rutherford and his colleagues Geiger and Marsden find is that occasionally one of these alpha particles actually bounces back off these gold atoms. And Rutherford actually describes this as the most incredible thing that ever happened to him in his life. He said, I think the famous quote is, "It's like you fired a 15 inch shell at a piece of tissue paper, and it came right back at you". And what this really shows is that Thompson's wobbly sponge-like atom is not the right model. Actually, what the atom is like is that at the very center, there is this tiny, very concentrated, positive electric charge. And occasionally, these alpha particles are coming very close to it and getting knocked backwards. So this then leads to the modern sort of cartoon model of the atom that we know about in schools, this sort of solar system like model.

[Melvyn Bragg] Thank you. ... Victoria Martin, Thompson showed that electrons can be separated from atoms, and from quite early on, that proved an essential tool. Can you tell us something about that?

[9:55]
[Victoria Martin] Okay, so we're jumping on a bit ahead here to experiments where we use electrons on their own, not inside atoms, but on their own, to look at the properties of matter and kind of more up to date with particle physics that I work on. So, electrons, as Harry's already said, are very, very light, which means they're quite easy to accelerate. You can give them quite a lot of energy, and therefore they can move very fast. We can use them as colliders. So we can collide them into, for example, either pieces of material or into other electrons or into other kinds of subatomic particles. And when we do that, we can work out the structure of whatever they're colliding into. So if we collide them into metal, which is made of atoms, we can start to look at the structure of metal. We can look at the crystalline structure of metal. If we collide them into individual protons, we can use them to find out the structure of a proton and if we collide them with electrons, we can start to actually look at not electrons themselves, but other subatomic particles that we've since learned about from doing experiments over the last 60 years.

[Melvyn Bragg] Why has so much of our knowledge come from smashing them together?

[Victoria Martin] We've been doing collider physics, I think, for the past 70 years now, and some of the first collidors were just using electrons. More recently, in the the 1990s, we had a very large collider, which we actually called the Large Electron Positron Collider. Now, I'm sure we'll come and talk about what positrons are, but basically because we can get them up to very high energies, and that means we can get a lot of energy into the collision. And when we have a lot of energy in the collision, because energy is conserved, we're going to get a lot of energy out of that collision. And even though you put electrons into the collision, it's not just electrons that come out. It turns out we can get a whole spectrum of different particles. And that has led us to the whole field of particle physics that we know now. So electrons were really the key for opening up a lot of our knowledge of how the universe works down at the tiny, tiny scale of the electron.

[Melvyn Bragg] So, apart from the atom being the smallest thing known, inside the atom are smaller things, and then inside the electrons are presumed they're smaller things....

[Victoria Martin] Ah, we might come onto that.

[Melvyn Bragg] We will come on to that. Thank you very much. Frank, we come to Paul Dirac ... to learn about electrons. He didn't use colliders. He used pencil and paper. Can you tell us about his contribution?

[12:38]
[Frank Close] Yes, well, he was a theoretical physicist, which proves that theorists actually do have some use. He was trying to understand the electron as the most fundamental particle known, using the two great theories of the 20th century, which were the quantum theory, which describes very small things on the atomic scale, and Einstein's special theory of relativity, which deals with things when they're moving very fast. And as Victoria alluded to, it's very easy to make electrons move very fast and so you need relativity to describe them when they're doing that. And what Dirac discovered was that he couldn't achieve that by writing a single equation. In a very profound and deep way the mathematics seemed to require this single equation to end up as four very intimately linked equations.

[Melvyn Bragg] When you said "the mathematics required" you're sounding [like] the mathematics as a person in the corner.

[Frank Close] Yes. It is very strange that what we will see is that by scribbling equations on a piece of paper, the equations turn out to imply things that Dirac hadn't anticipated. And then an experimentalist goes out and discovers these very things. It's as if the theorist, or the equations. knew nature before we did. And I still find that very profound and disturbing, but that is the nature of science. And that is what Dirac did. The thing was that the fact that his single equation had bifurcated twice over raised the question, well, what's going on here? Well, the first doubling, if you like, was interpreted as showing that the electron, in addition to just being a lump of charge, which is what we've primarily talked about so far, also is like a little magnet. And we think of magnets having a north pole and a south pole. So we have a mental image of the electron being a north pole and south pole, or spinning clockwise or anticlockwise. Now, I stress these are mental images. It's very useful, even as a professional scientist, to think of imagery that you're used to and scaling it down, even though there's very profound things going on in the quantum world. The mathematics said there's this strange duality to the electron. And indeed, experiment confirmed that, because when you take the spectra of various atoms and put those atoms in a magnetic field, the spectral lines in some occasions sort of split in two which show that there was something magnetic going on about the electron. And Dirac's equation now explained that - by the first bifurcation.

[Melvyn Bragg] Is there any focus on here on spin?

[Frank Close] Yes, this was the word that was given to describe this bifurcation. They said "we call this spin". It can spin clockwise or anticlockwise to make, if you like, North Pole or South Pole. And that was really what I was alluding to when I said mental imagery, because the little point-like electron presumably cannot in any real sense spin. But it's useful to keep picturing in your mind that as an image to hang on to. So that was one doubling, but what about the other doubling? The other doubling seemed to be describing his negatively-charged electron having negative energy, which doesn't make any sense at all. What is negative energy? Until it was realized that you could reinterpret that as positive energy of a positively charged electron, now known as the positron. And indeed, that was, if you like, the discovery on a piece of paper of what we now call antimatter. And I'm sure that Harry can tell us much more about this. But this comes back to the question that you raised of me, or the challenge that you've made of me. I find it astonishing that the mathematics knew of antimatter before we discovered it.

[Melvyn Bragg] Over to you. I mean, Frank's handed you this difficulty on a plate Harry.

[16:47]
[Harry Cliff] So Paul Dirac, he comes up with this equation, which is now known as the Dirac equation, I don't think he called it that himself. That would have been rather... you have to wait for someone else to name an equation after you, I think. And the first thing he does, actually, as Frank says, this equation implicitly includes spin and explains where spin comes from. The other thing it does is it beautifully matches all the experimental data of atomic spectra so these are characteristic frequencies of light that atoms absorb and emit when you heat them up, for example. So he's really, really pleased. But then he discovers, as Frank says, these sets of solutions that appear to be describing these negative energy particles. And this comes as a huge blow to Dirac, because he thinks this beautiful equation I found is going to be destroyed because this is nonsensical - how can you have a negative energy particle? As Frank says, he then reinterprets this as well. You can think of this maybe as a positively charged electron with positive energy.

[Melvyn Bragg] You've got a bit too fast for me, to put it mildly. He just decides that this can happen. Is there any evidence for it? It suits him better to...

[Harry Cliff] He actually goes through various permutations to try to get rid of these solutions, and he finds that he can't get rid of them. So what he realizes is these negative energy solutions, you have a negatively charged electron with negative energy, it turns out that's mathematically equivalent to a positively charged electron with positive energy. You have to take my word for it, unfortunately, without getting out a pen...

[Melvyn Bragg] I've got no other option...

[Harry Cliff] But, I mean, Dirac actually spends about three years trying to figure out what on earth these positively charged electrons are, because no one's ever seen such a thing in nature. And eventually, he comes to the conclusion, in about 1931, that these things must exist, because his equation works so beautifully in all other ways. He actually makes this very audacious prediction and says, I believe there are positively charged electrons out there, even though they've never been seen. And then this is, I think, as Frank said, one of the sort of most magical episodes in the history of science. Very eerily, a year later, a scientist, american scientist called Carl Anderson, he's working with a device called a cloud chamber in California. So a cloud chamber is essentially a vessel with some water vapor in it. And it was the first device that could actually image individual subatomic particles. So when, say, for example, an electron goes through one of these chambers, it creates this trail of water droplets behind it, almost like the contrail of an aircraft. You can see these things traveling through the chamber. And he has one of these things at his lab, and he puts it in a magnetic field, and he sees a particle that looks behaves just like an electron, but it's curving in the wrong direction. So it's bending in the opposite direction in this magnetic field, indicating that it has positive, not negative, charge. And so this is really what's incredible about this episode, that Dirac has kind of conjured the existence of this particle purely through applying quantum mechanics, relativity, and mathematics. So he predicts the existence of a type of matter, what we now call antimatter, before anyone had even really seriously imagined such a thing might exist.

[Melvyn Bragg] Can you take up antimatter, Victoria?

[19:35]
[Victoria Martin] Yeah, I know it seems strange to say and Harry's explained it...

[Frank Close] I have to interject, "not literally, no". [laughter]

[Victoria Martin] OK. The reason that Frank has made that joke is if one lifted up antimatter, one would just poof out of existence. And that would not be a very pleasant thing to happen in the studio right now. And if we take a pair of matter and antimatter - so since we're talking about the electron today, if we take an electron and the positron and you put them together, they would annihilate and they would annihilate not into nothingness because they both had mass, so they both had energy from E equals MC squared. That tells us if you have mass, you have energy, so they would annihilate into energy. But It wouldn't just be any kind of energy. The particular kind of energy you get when you annihilate an electron and a
positron is a photon - a particle of light, and it will have a very specific amount of energy. Its energy will be equal to the sum of the energy of the electron and the positron that they had initially when they collided together.

[Melvyn Bragg] Can you tell listeners what shape an electron takes and how big it is?

[Victoria Martin] Ah. Yes. Well, I mean, I think some point earlier you said that the electron might be made of something smaller, but as far as we know, no, it's not. So if you ask me what size an electron is or what shape it is essentially has no size and no shape; it is a point like particle.

[Melvyn Bragg] Sorry... a point-like particle. Which means what?

[Victoria Martin] Basically that it has no size.

[Melvyn Bragg] That's very difficult...

[Victoria Martin] It's very difficult for *us* ... So, of course this is a theoretical prediction, and as an experimentalist, one of the things we like to do is of course [to] test that. And we have tested that and the collisions that we talked about earlier are one way that you can test the size of an electron. And we found that it's smaller than ten to the -18 cm so very very very small. But we just don't have the experimental precision to go down any smaller. Now, it could be that if our understanding is wrong, if our theoretical understanding is wrong, maybe ... it does have a size. So it could be made of, for example, of a vibrating string, which is something that String Theory suggests, but we really don't know. So I think of it just as a kind of vanishingly small spot in three dimensions.

[Frank Close] To add to what Victoria is saying here, that all we can say for certain, as she said, is that we can resolve distances as small as 10 to the -18 cm or so.

[Melvyn Bragg] Is there any way that a normal human being can understand what that number is?

[Frank Close] Probably not... But trust me...

[Melvyn Bragg] I trust you...

[Frank Close] All we know is that even if you can't imagine that small number, the electron is even smaller than that. And if we had higher resolution, we would be able to maybe answer your question - what its shape is and how big it is. Or we might only be able to say and it is even smaller than that. And it's in that sense that when Victoria says point like that is the language that we use: To the best of our experiments, it's like a point.

[Melvyn Bragg] I just want to stay with Frank for a second. So the electron is so small, yet it has the same charge as a larger proton, does it?

[23:16]
[Frank Close] Ah...That is very profound. The answer is true...that ...atoms are electrically overall neutral unless they're ionized, that the negative charge on a little point-like electron perfectly balances out the positive charge on the protons in the

nucleus in the middle. And the protons, as you alluded to, they have a measurable size, they have an extent that we can, not only measure, but we can, using beams of electrons as Victoria said earlier, probe inside ...and see that inside the proton there are smaller things called quarks. And the weirdness is that a proton is made of three quarks and these quarks carry fractions of electric charge two thirds positive or one third negative. And if you have two of one and one of the other that balances out to plus one, which is a perfect balance for the negative electron. Why [should it] be that three quarks which supposedly have nothing at all to do with electrons, conspire in this way to balance out the electron? If you have the answer to that, listeners, please write in and explain. But to show how remarkable this neutrality of atoms actually is, each breath that we're taking, we're breathing in a huge number of atoms of oxygen and in each of those atoms there are negatively charged electrons. So the negative charge on the electrons in the oxygen atoms in each breath you take is about 10,000 Coulombs. Now, what does that mean? It means that that would be enough to ignite 1000 bolts of lightning...

[Melvyn Bragg] So, why don't we all blow up?

[Frank Close] There's no blow up and there's no spark flying around here in the studio because in each breath there is also this perfectly counterbalancing positive charge. The thing that, as Harry said earlier, led Thompson to ask where is the positive charge that must balance it all out? So every breath you take proves this neutrality of atoms and it is one of the great mysteries that we still don't have a complete answer to.

[Melvyn Bragg] Harry, can you take that on?

[Harry Cliff] Yeah, well, I'm not sure I have an answer to that question unfortunately. I was going to come back to the shape of the electron because there actually are experiments, low energy experiments, which are not colliders, but experiments that are done in university labs and basements. For example, there's one at Imperial College where they try to measure the shape of electrons. And when we talk about the shape, what we mean is - is the electric charge sort of spherically distributed? Is it sort of completely symmetrical, or is it a bit stretched in one direction? Does the electron have, like, more of a cigar shape? And I won't go into how these experiments work because they're very clever and complicated, and I'm sure I fully understand them. But I went to see some of the scientists a few years ago, and they told me that they had measured the shape of the electron to an incredible precision and found that it was very, very, very round indeed. And to give you a sense of how round, I said, if you blew up an electron to the size of the solar system, it would be spherical to within the precision of a single strand of human hair. And these experiments are always going further and trying to sort-of test whether they eventually see some distortion in the shape. And the reason this is actually interesting is sort-of something quite deep and fundamental about what electrons really are. And we sort of haven't really touched on this yet, but we've been talking about them as particles. So you might be imagining them as little billiard balls or something, zooming around. But actually, modern particle physics tells us that actually weirdly particles are not the fundamental building blocks of the universe and that all particles are actually disturbances in these more fundamental objects known as quantum fields. And you can think of a quantum field as a sort of well, we've all experienced a field. If you ever held a two magnets, say, taken the north pole of two magnets and push them together, you feel this physical repulsion caused by the magnetic field, in this case. And we know we're probably more familiar with the idea that light, for example, is a wave in the electromagnetic field. So the way you would broadcast radio over long distances by radio waves, which is a disturbance in this electromagnetic field, we actually think of electrons in a similar way. So there's something else along with the electromagnetic field called the electron field. And every electron is actually a little vibration in this underlying field, which is kind of a strange thought. It basically means that every electron in our bodies, every electron in the world around us is a sort of ripple in this invisible ocean that fills all of space, which kind of means that actually we're all part of the same object, which is rather strange.

[Melvyn Bragg] Is all this still happening inside the atom?

[Harry Cliff] Yes.

[Melvyn Bragg] So it's not a billiard ball, the atom, it's a sort of a hive of activity...

[Harry Cliff] Exactly. Yeah. So you can think of these electric

[Melvyn Bragg] So its a solar system - like a mini, mini, mini solar system?

[28:06]
[Harry Cliff] We have all these sort of like visual metaphors that help us come up with a mental picture, but they're all wrong in some way, and no one's really got an accurate metaphor for what the atom is really like. And sometimes it's helpful to think of them as little planets going around the sun. Other times it's helpful to think of them as these disturbances, these waves that are in some kind of fluid almost. So both of these things are true at the same time to some extent.

[Frank Close] Just like the electromagnetic waves of light, we can also think of those as little staccato bursts of photons - particles. Sometimes it's better to think of the staccato bursts of the photons. Other times, the legato of the wave. It's both and neither at the same time. That's this strange duality of the quantum world.

[Melvyn Bragg] I'll say. Victoria, we get deeper into this. What's the Coulomb force, and how does that relate to electrons?

[Victoria Martin] Okay, I think we've already mentioned the Coulomb force before; I think Frank mentioned it. The Coulomb force is the force between any two electrically charged objects. And it's very important, for example, inside an atom. So an atom has this positively charged nucleus. And as we've talked about several times, electrons kind of well, one picture of them is them kind of orbiting around the core, this nucleus. And, as we've discussed, the electron has a negative charge and the proton has a positive charge. And if the two electrically charged objects have opposite charges so, for example, the case in the atom, when one is negative and one is positive, then the Coulomb force is attractive. And this is actually one way that the electron keeps orbiting around the nucleus of the atom. But you also get a Coulomb force between two objects with the same charge, for example, they will repel each other a bit like as we were talking with, it's not the same, but with magnets, they will repel each other. Something that I think people are probably quite familiar with is taking a balloon and rubbing it on something and then sticking it to the ceiling. And actually, that uses the

Coulomb force because what you do when you rub the balloon is you're actually removing or encouraging some of the electrons that make up the balloon. So the electrons inside the atoms that make up the balloon, some of them are taken away. And so the balloon now has a positive charge. And, you can't see me, but I'm pointing to the ceiling. We put it up on the ceiling, just, I think, for fun. They will be attracted to the electrons on the ceiling which are on the outside layer of the atoms. And therefore, we will see that attraction between the two. Another place where we actually see it is if we jump. So there is a force that keeps us on Earth called the gravitational force, and it pulls us down. So when we jump, why don't we just keep on traveling down through the floors towards the surface of the Earth or even further down? And actually, it's the Coulomb force again that stops that happening because our shoes or our feet are made, again, of atoms with electrons on the outside because it's the electrons that go on the outside of the atoms, and so is the floor and so these two things repel each other. So actually, this Coulomb force is all around us and actually informs a lot of our kind of everyday experience. But again, a lot of this is back to electrons. This is another reason they're really so important in our everyday experience.

[Melvyn Bragg] Can we bring this together in one sense, Frank? How do you reimagine the arrangements of electrons in an atom?

[31:58]
[Frank Close] Well, electrons are held in the atom, as Victoria said, by the Coulomb force, with the positive nucleus at the middle, and their negative charges on the electrons [are] holding them in place. But as Harry said, that we can think of things as particles or as waves. And thinking of them as waves on this occasion is the best way to understand how they act inside the atom. Think of a rope. If you shake a rope and you will have a wave going on the rope, if one end is tethered somewhere. The higher the energy that goes in there, the shorter the wavelength of the waves in the rope. So it is with electrons, the higher their energy, the shorter the wavelength corresponding to them. Now, in an atom, they are going round and round. So it's like a rope where you're trying to make the rope wobble, but attach the far end of the rope to the end that you're holding to make a complete circle. And you can only do that if the far end of the rope is oscillating perfectly in agreement with your end, so that it's up when you're up, it's down when you're down, to be able to tie them together. So the electron waves as they circle around in the atom, can only fit properly if they have a perfect number of wavelengths in a single circuit. And that is not easy to do. It can only happen in certain configurations, and these different configurations have different energies. So an electron in an atom, to make the waves match perfectly is like a series of rungs on a ladder. You can be on a rung, but you can't be halfway between a rung. And if an electron is on a high level or high energy rung, and it drops down to a low energy rung, the spare energy is radiated as light, and that is where the spectral lines come from. So it's the fact that the spectral lines are discrete rather than continuous that shows that the energy levels of electrons in atoms are like rungs on the ladder. And the reason why they're like rungs on a ladder is because they are light waves inside the atom, and the waves have to match perfectly.

[Melvyn Bragg] It's a brave new world, this, isn't it? Just for me.... Harry, what are muons? ... And how do they relate to all this?

[34:12]

[Harry Cliff] It's a good question. So, yeah, muons were discovered by the same American physicists who discovered the positrons, this guy, Carl Anderson, and his colleague Seth Neddermeyer. So, a few years after the positron, they're still using cloud chambers, and they're on top of a mountain in Colorado called Pike's Peak, which is a very beautiful pink granite mountain. And they see a new particle in their cloud chamber, again a curve in the magnetic field, which behaves, again, very like an electron, but it appears to be 200 times heavier. So it's almost like a copy of the electron, but much, much more massive. And no one really knows what on earth this thing is. There's a physicist called Isidor rabbi who's a Nobel prize winner, who famously retorts "Who ordered that?". In other words, it's like a pizza that's turned up at your house, but you didn't order it. What's this thing for? It doesn't seem to form atoms; it's not part of ordinary matter; it comes from cosmic rays in outer space. But no one really understands what on earth these things are. And that's still true today, actually, more or less. What we've discovered in the last almost 100 years since then, I suppose, is that electrons are part of a triplet of particles with the same properties, but they get heavier each time. So the muon is the second, 200 times heavier. And there's something called the tau, which is about three and a half thousand times heavier than the electron. Now, these three particles, they have the same charge. They interact with the forces in the same way. The electron is the only one that's stable. So electrons, once you create one, it hangs around forever, live forever. Muons and taus decay very quickly in millions of a second or less. And there's a mystery. These things clearly are related to each other, but we don't really know why they exist. And again, if you can figure that out, you'll definitely win a Nobel prize.

[Melvyn Bragg] Victoria, do you think that the electrons are fundamental particles?

[Victoria Martin] Yes. I sound a bit philosophical there. At least our current understanding is that they are fundamental particles, and that's all the evidence we have. So all the evidence that we have points to the fact that they're fundamental particles and something that Harry was talking about, about trying to measure how spherical they are and them being as spherical as - what was your analogy again?

[Harry Cliff] If they were the size of the solar system, they are spherical to within a strand of human hair, I think.

[Victoria Martin] So if they weren't fundamental, if they weren't made of anything smaller, then we do expect them to be spherical. If they were made of something smaller, I think we would start to see different kind of shapes there. But, of course, there are people that like to think kind-of beyond, could they be made of something smaller? And we've definitely tried to do experiments also to kind of break apart an electron. And if you could break it apart into pieces, then that would obviously tell you that it's made of something smaller. But we haven't managed to do that yet. But there are theories, really just theories, that they could be made of something smaller, including superstrings, which is something that comes from String Theory. And in String Theory, in which I'm not an expert, they would just be made of tiny vibrating strings. So again, they would be very super small, I mean, much smaller than our experiments could see at the moment. But right now, and personally, I believe the electron is fundamental and has nothing inside it but itself.

[Melvyn Bragg] So, Frank, what do we not know about the electrons that you would like to know or you think we might get to know?

[37:43]
[Frank Close] How long have we got? As Victoria has alluded to, is there anything smaller than an electron? Is an electron indeed the last layer of the cosmoconon, or is there something beyond that? One of the problems another question is why does the electron have the particular mass that it does have and not some other? And why is its mass so small? Because one of the problems with trying to imagine the electron being made of smaller things is that the electron we know is very, very small, which would lead us to expect it to be very, very heavy. Short distances and high energies and high masses tend to go together. So it's very difficult, theoretically, to make a model of an electron made of smaller bits while keeping it light. So that's another reason why I think there's something special this time around. But Harry mentioned the muon, which is like a heavy electron, and yet it's more than that. And it's more than that in the following sense: If the muon was just an excited form of an electron, meaning a heavier version of an electron, then you would expect it to get rid of all of that spare energy by radiating light and becoming an electron. That does not happen. There is something that is more than just heaviness that distinguishes the muon from the electron. So the electron has some "electronness". We call it flavor, we put it in the equations. But what it actually is, I don't know. And then to me, the great mystery that we've alluded to earlier. Why does the charge of the electron so perfectly balance the positive charge of the nucleus made of stuff which has apparently nothing to do with electrons, so that gravity overall rules the large scale universe, and the electric charges are all buried inside atoms, perfectly balancing out, hiding themselves away.

[Melvyn Bragg] Do you have a solution to this, Harry?

[Harry Cliff] No, but actually we are working on it. So I work on the Large Hadron Collider, like Victoria, and we're doing experiments to try and understand these questions. So actually I work on measurements where we look at how often certain particles decay into electrons and how often they decay into muons. And this is a way of trying to get at this. What is it that intrinsically makes an electron different from a muon, because if you see some difference in these decays, that could give you a clue. And as Frank says, I think the real mystery is we have electrons, muons and taus. We have these things called quarks. It looks like they seem to be different, but they seem to be related to each other by some kind of deep principle and it is probably not so much that we're trying to find out what's inside them, it's what is the principle that relates all these things to each other? Is there some deep symmetry in the laws of nature that means these things must exist? And that would then explain why the quarks charges balance with the electrons, as Frank said, and explain what a muon is and how it relates to the electrons. So it's by looking at the patterns in these particles that we might get a deeper understanding ultimately.

[Melvyn Bragg] Do you want to develop that, Victoria, where we're going to go next to the electrons?

[Victoria Martin] Relating back to something that we talked about very early on in the program, we are trying to find these deep patterns between electrons and the muons and the other particles that we see, and we actually use electrons to do that. So in the future, we are planning, if we can get away with it, to build a super large collider that would use electrons and also the positrons, the antimatter particle of the electron that we've talked about, and essentially smash them together. And this will produce a lot of energy in the collision. But the nice thing about producing all of that energy is you can make some new particles. So actually, from putting an electron and a positron together, ... they annihilate, and that can give you a muon and the antimatter component of the muon as well - that positively charged muon. But we can also do that with perhaps and make particles that we don't yet know about. And these might give us some insight into a lot of these questions that we've been asking. Why is the charge so perfectly balanced? Why are the masses of the particles the way that they are? And, like, what is the underlying structure of the way that all of these things fit together? Because that's still a mystery. So the electron was the first thing. We've found out a lot of new particles and new phenomena since then. But how do they all fit together? That's still a very open question.

[Melvyn Bragg] Well, as soon as you know, you can all come back. Yes, that was absolutely terrific. Thank you so much. That was just great. Thank you very much, ... Victoria Martin, Frank Close and Harry Cliff and our studio engineer, Jackie Marjoram.

And the In Our Time podcast gets some extra time now with a few minutes of bonus material from Melvyn and his guests.

[Melvyn Bragg] What would you like to have said that you didn't have time to say? Just start with you, Harry.

[42:54]
[Harry Cliff] I started talking about the shape of the electron and talked about this idea of quantum fields, that the electron is like this ripple in this field if I didn't really explain how those are connected. And there's this very strange fact that an electron isn't just an electron. If you sort of zoom in on an electron, what you start to see is it's surrounded by these ephemeral particles, what we call virtual particles. So actually, all the other particles that exist contribute to what the properties of the electron that we measure. So, like, for example, we talked about quarks...
If you zoom in on an electron, you see fleetingly, the effect of these quarks that are coming in and out of existence, almost like a cloud. You have the electron in the middle, but then you have these virtual ephemeral particles around it, which we can't sort of directly observe, but they do have an effect. So when we're measuring when scientists measure the shape of the electron, they're essentially trying to figure out, are there other things around the electron that are sort of altering its shape? And this is interesting, because if you do measure that the electron isn't spherical, that could, as Victoria said, tell you that maybe there is something smaller in the electron. It could also tell you that there are some new particles that we've never seen before that are squashing the electron effectively. They're part of this kind of virtual cloud around it. So it's a very weird thing. But basically, the magical thing I think about this is that an electron isn't a pure electron. It's actually made of all the particles in nature at the same time.

[Victoria Martin] Yeah, everything at once.

[Harry Cliff] So an electron, in a way, is a sort of microcosm of everything. And that's why they're such fascinating things to study, in part.

[Melvyn Bragg] Frank, you look poised for talk.

[Frank Close] I was just stimulated by what Harry was saying... and it's now completely gotten from me. But the question, when you proposed it, is "what is the shape of an electron?"" And I suppose an instant answer is, well, it's spherical. Because if it wasn't, why wouldn't it be? In the sense that if there's nothing else around, nature doesn't care, doesn't distinguish between the three dimensions. So spheres are the natural things that you would expect, like, you know, the sun is spherical. When things are not spherical, you ask the reason, why aren't they spherical? I mean, the Earth isn't spherical because, well, it's rotating around, so it's slightly squashed at the poles because of centrifugal force. And, of course, when you look at it in detail, there's lots of peaks and dips on the surface. You and I aren't spherical because we are made up of atoms that are held by electromagnetic forces. And they have shapes and they link together in special ways. So when things aren't spherical, it's giving you a clue that there's something else. So if we were able to find indeed a lack of sphericity in the electron, then that would be very important, showing that there is something going on. The question then is what is the something that is going on?

[Melvyn Bragg] Do you want to come in on this, Victoria?

[Victoria Martin] I wanted to bring in something that we've danced around a lot, which is Quantum Electrodynamics, which is how the electron interacts. And basically we've been talking about this, the whole program without actually saying these words or talking about it directly. It's this idea that Harry brought up about there being fields and the electron kind of being a wave inside the field. But an electron itself or this field is not particularly interesting unless it does something (and we've been talking about all the different things it does) but fundamentally the thing it does in quantum electrodynamics is emit photons, these particles of light, or absorb photons, these particles of light. So, yeah, I mean, that's almost the whole thing that we've been talking about without actually using those words.

[Frank Close] Quantum Electrodynamics that Victoria mentions ... touches on the question, really, what does an electron look like when you look at it? And the answer is, it depends on how closely you look at it. The electron is a lump of charge which gives rise to an electric field. And the energy in that field can be manifested as particles and antiparticles surrounding it. And the closer you look, the more you're aware of this surrounding stuff. It's like a fractal that you keep seeing the same thing at deeper and deeper and deeper levels. And so the electron in reality is a very complicated object. The electron in Dirac's equation was just a little point like thing. But that was Dirac's equation; [in] Quantum Electrodynamics, which he himself actually developed two or three years after his original equation, the electron that appears in that is a very complicated thing, surrounded by electric fields, surrounded by clouds of particles and antiparticles. And the closer you look, the different perspective you get.

[Melvyn Bragg] Harry?

[Harry Cliff] Yeah, that's right. Actually, Quantum Electronomics... one of the things that's amazing about it is I think it's right to say that it's the most precisely verified theory anywhere in science. So one of the sort of the flagship measurement is of something called - essentially what Frank's talking about, the magnetism of the electron - and you can predict the magnetism of the electron from this theory of quantum electrodynamics. And you can do this with huge supercomputers. And you get a number that I think you calculate to something like twelve significant figures to sort of a part in a trillion, essentially. And then you can do a very, very clever measurement in a laboratory where you measure how magnetic an electron is very, very precisely, and the numbers agree to, I think it's something like twelve or eleven significant figures now. So this is an absolutely unbelievable level of agreement between [them].

[Frank Close] To take your analogy of the solar system, it is a precision level, somebody once said like measuring the width of the Atlantic to the width of a human hair. So that works. QED is a good acronym. [laughter]

[Melvyn Bragg] I'm surprised I'm still here talking to you, really.... [laughter]

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In our time with Melvyn Bragg is produced by Simon Tillotson.