THE PROTON - Curated Transcript of BBC In Our Time podcast

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[Melvyn Bragg] Hello. There are enough protons in the sun for it to last a thousand billion years, and it's only about halfway through them, so that's a relief. The properties of protons there, as on earth and throughout the universe, are those that make chemistry, biology and life itself possible. They've existed since a split second after the Big Bang and are found in the nuclei of all elements. Hydrogen, by far the most abundant element in the universe, is a single proton with one electron. Stripped of electrons, those protons can be accelerated to smash other nuclei to reveal more of the secrets of particle physics, and they can be used in the treatment of some cancers. And while much is known about protons, much remains to be discovered. With me to discuss the proton are Frank Close, Professor Emeritus of Physics at the University of Oxford, Simon Jolly, Lecturer in High Energy Physics at University College London, and Helen Heath, Reader in Physics at the University of Bristol.

[Melvyn Bragg] Frank Close, what's a proton?

[Frank Close] Well, a proton is one of the seeds of atoms. Probably the story really begins around the end of the 19th century, a time when the idea that matter is made of atoms was established. But the belief that atoms are the smallest pieces was beginning to fall apart, probably almost literally, because in Cambridge, JJ Thomson discovered that inside atoms are little particles called electrons. Now, electrons are probably most familiar as the carriers of electric current, because electrons are electrically charged. Electric charges come in two varieties, plus and minus. And electrons, by convention, are negatively charged. So inside all atoms, there's a lot of negatively charged particles. And yet atoms overall, matter overall, isn't electrically charged. So by the start of the 20th century, people realized there must be something positively charged inside atoms to counterbalance this negative stuff. And these positively charged carriers we now call "protons" and the question was, what are they? Where are they? How does it all work?

[Melvyn Bragg] Can you give us an idea of the size? Because I love this sort of astonish-me-stuff. The size of the things we're talking about, the protons, and how people like you get to see them and know they're there.

[Frank Close] Well, the size, I mean, an example I gave: Scale an hydrogen atom up to the longest hole in the golf course. So the distance of the hole is about 400 meters that you're trying to get the ball in, and the size of the hole that you're trying to get the ball into that is like the size of the proton, if the teeing off point is where the electron on the outside is. So if you can imagine, scale, anything up to that, that shows you how small the proton is inside an atom. As for the atom itself, [for] those of us who have hair: about a million atoms across one another will fill [the width of] a single hair.

[Melvyn Bragg] You have to take a deep breath, don't you? And so this is technology at its finest, getting you there?

[Frank Close] That's certainly true. But in fact, the ways that this was sussed out by Ernest Rutherford between about 1912 and 1920, just about a century ago, was, with hindsight, relatively simple. But the simplicity was, in a way, the genius. He realized that nature was very nice. It provided little subatomic bullets called "alpha particles" that we now know [] are bits of atoms that [have been split] off. But all that he needed to know was [that the alpha particles have] got positive electrical charge. And because positive charges repel positive charges (like charges repel), if these alpha particles were fired towards atoms, then the positive charges inside those atoms would repel the alpha particles. And so he...

[Melvyn Bragg] How did he fire them at the atoms?

[Frank Close] Nature did that for him, if you like. What he was wanting to see was what happened after they had passed by the atom...

[Melvyn Bragg] Sorry, Frank. How did nature do it for him?

[Frank Close] Nature, randomly in some cases, causes radioactivity to happen, which means an atom can spontaneously change from an unstable form to a more stable form. In the process, it emits stuff. In particular, it might emit these alpha particles. How and why it happens is the deepness of quantum mechanics, which I hope you will not ask me about. But for him, what he did was he, first of all, fired these things at the atoms of heavy elements like gold. And all we need to know about alpha particles is that they're very light on the scale of a gold atom, but they're much heavier than a hydrogen atom. So when you're firing an alpha particle at gold, it's like firing a little elastic ball at a big football. It bounces off, it bounces back at you. And that was the surprise that Rutherford had, that these things bounced back. So he realized that the positive charges in gold must be concentrated in a big lump in the middle. That was the discovery of the nucleus. Then he went to the other end of the periodic table, such as hydrogen, that you mentioned in the introduction.

[Melvyn Bragg] The lightest…

[Frank Close] The lightest. And in the case of hydrogen, we now know there's a single proton, which is only about one quarter the mass of an alpha particle. So on this scale, the alpha particles [are] like the big football and the protons [are] like the little elastic ball. So when the alpha particle arrived, it kicked the proton out. And Rutherford called these things "H particles", H for hydrogen. And then the next step was he discovered that if he fired things like alpha particles at oxygen and nitrogen, which were also light, these H particles got chipped out of there as well. So his final insight was these things, which he then called "proton", are the fundamental carriers of the positive charge. You cluster more and more of them together, and you get more and more positive seed to attract electrons to make heavy and heavier elements.

[Melvyn Bragg] Thank you very much indeed for that and [I'm] much relieved now. We're on our way. Simon Jolly, can you tell us how you would describe an atom?

[Simon Jolly] Ah..It depends on how sophisticated you want your picture to be. Prior to Rutherford's discovery, it was thought that there was this plum pudding model, this uniform collection of positive and negative charges. Rutherford's discovery led us down the route to the model of the atom where you have this cluster of positive charges, charges at the core, and this orbiting halo of electrons around that positively charged core. So the simple way to imagine it is like a tiny planetary system with the sun is the nucleus, and then the planets are the orbiting electrons. The complexity starts to come in when quantum mechanics falls into the picture, because you start to describe subatomic particles not as little hard objects, but as actually tiny wave packets. So they're not localized in space. They start to have a distribution. So the electron cloud around the nucleus is exactly that. It's not discrete objects. As they orbit the atom, it actually forms this halo around the atom. So the point at which our macroscopic picture of the world of imagining solid objects orbiting other solid objects starts to break down a little is with the electrons as they orbit the nucleus. But a simple way of picturing it as the Rutherford model of the atom, with a solid nucleus, with protons and neutrons, and then an orbiting cloud of electrons around it.

So what's inside the atom?

[Simon Jolly] You have these two parts. So at the core, the nucleus is made up of positively charged protons and neutral neutrons, and they're bound together extremely tightly. And then this cloud of electrons, which orbit around the nucleus, are held there by the attraction, the electrical attraction, between the negative charge on the electrons and the positive charge from the protons. The nucleus itself is not actually bound together by the electromagnetic force. There's another force called the "strong nuclear force", which helps to bind positively charged protons together, because otherwise, if there wasn't another force, they would simply force each other apart by electrostatic repulsion. So the nucleus is bound extremely tightly with the strong force. And then the electrons in their orbit are held in by the electrical attraction.

[Melvyn Bragg] It's a little world, isn't it? It's a little universe down there or in there, all around us.

[Simon Jolly] That's correct, yes.

[Melvyn Bragg] Billions and billions and billions of little universes in this studio.

[Simon Jolly] More than you can imagine.

[Melvyn Bragg] I can't imagine even billions and billions.... What's the link between the proton and differences between chemical elements?

[Simon Jolly] The proton is really the particle that defines the chemical element. So what sets one chemical element apart from another is not just the mass, the fact that hydrogen is the lightest, helium is heavier, and then up to lithium and so on. It's also how they form bonds. And the way that one atom bonds with another, most commonly, is through the sharing of electrons. Now, the number of electrons that each atom has has to match exactly the number of protons in a stable atom. It's possible to add or remove electrons, and then the atom becomes charged, and that's what we call an "ion". But in the most common type of atomic bonding, called "covalent bonding", it depends on the number of electrons that you have in the outer part of the atom. Now electrons actually like to cluster together into groups within the atoms. So at the lowest energy level within an atom, you have two electrons. Now, if you think of something like hydrogen, hydrogen has now only got one proton in the center and one electron orbiting, which means there's a gap. So that means hydrogen actually likes to form a single bond. And then covalent bonding is the exchange of that electron with another chemical. And so the number of bonds that each chemical can form is defined by the number of protons that you have in the nucleus.

[Melvyn Bragg] Fine. I think I'm still on board. Helen Heath, it was once thought that the protons were fundamental particles. How and when did that change?

[Helen Heath] Well, there are lots of pieces of evidence that the proton isn't fundamental. Initially, there was work done with cosmic rays. So cosmic rays are naturally accelerated particles that come into the upper atmosphere, and there was a lot of early work done studying their interactions with matter. I feel obliged to mention people like Cecil Powell, who was at Bristol University, who did a lot of the early work on this. And in those collisions, they found lots of...particles, essentially a zoo of different particles. And in trying to understand those, they started grouping them together, particles that had similar properties, for example, similar masses. And that led people to try and think about why there were these patterns in this zoo of particles that you could see. And Murray Gel Mann and George Weig came up with this idea of a quark model.

[Melvyn Bragg] Quark?

[Helen Heath] Quark, yes. So that this zoo of particles were actually different combinations of smaller particles called "quarks". And the quarks had some unusual properties, or they would have had to have some unusual properties, one of which is that they would have a charge that was a fraction of either the proton or the electron's charge. And we've never seen a particle with a fraction of the proton [or] electrons' charge in a laboratory. We've never been able to measure something with a fractional charge moving through our labs.

[Melvyn Bragg] You've never seen a quark?

[Helen Heath] Well, it's not quite true. We've never seen a quark out on its own. They like to go around together, and they like to go around in particular combinations... There are a number of combinations that we've seen now, but until quite recently, the combinations that we've seen were three quarks together, which is called a "baryon", or three antiquarks together, which is an "anti baryon", and a combination of a quark and an anti quark, which we call a "meson". And the proton is the lightest mass baryon and it consists of two types of quark that give it its external properties, such as its charge. And those are the "up quark", which has a charge of plus two thirds of the electron charge, and the "down quark", which is a charge of minus a third. So we've got plus two thirds, plus two thirds, minus a third, which makes plus one. And that's our proton.

[Melvyn Bragg] So can we go back to, what does that make our view of the proton now?

[Helen Heath] So our view of the proton now is that we've got these, these three quarks, two ups and a down, which are what we call the "valence quarks". So essentially those, it's an analogy with chemistry. So in chemistry, the valence electrons are the ones on the outside that give it the atom its chemical properties. And the valence quarks of the proton give us the outward looking properties of the proton, for example. So it's electronic...

Heavy nods from the two gentlemen on my right.

[Helen Heath] Well, that's encouraging. [laughter].. But one of the interesting things about the proton is if you start to look into it, you find it's actually a lot more complicated than that. So, first of all, there's the particles that hold those quarks together, which are called "gluons", and then those gluons themselves can split to make quark-anti-quark pairs which appear and disappear, and we can actually start to see those. So the first experiment... really seeing the objects inside the proton were in the 1960s in Stanford in California. If you scatter electrons from protons, a bit like Rutherford scattering that Frank was talking about, if you scatter electrons from protons, then you start to see not just a whole big object, and proton is big on particle physics scales, but you start to see individual tiny scattering centers ... (point like things)... inside the proton. So we can actually confirm that there are objects inside the proton.

[Melvyn Bragg] Do you think you've reached the center of it yet?

[Helen Heath] Well, that's a very big question. Have we got the... Is what we think of now as fundamental, truly fundamental..? I think, I'd like to think not, but, you know, we have to keep looking.

[15:04]

[Frank Close] I suppose the best you can say is that at the present state of knowledge, we know of nothing smaller than the quark scale and we know nothing smaller than the electron scale. They are, in an analogy, the fundamental letters of nature's alphabet. That doesn't mean to say that in the future we might have more powerful microscopes that can resolve internal structure in them, analogous to the way that Rutherford discovered internal structure in the atom a century ago. But for the moment, that's where we are.

[Melvyn Bragg] Let's go back to the beginning, back to a nanosecond after the Big Bang, and then back to the sun. Come on, Frank, you're the man for this. What's the role of the proton in the sun?

[Frank Close] Well...

[Melvyn Bragg] ...For our listeners, the sun came a long time after the big bang.

[Frank Close] That's true.

[Melvyn Bragg] There's a direct connection.

[Frank Close] But protons came quite soon after the big bang, about a second or so. So protons were the first of the now-existing particles, if you like, that emerged out of the Big Bang, and they are, to the best of our experiments, stable. And so protons have been around ever since then.

[Melvyn Bragg] Do you mean when you say stable, you mean not moving, or do you mean they've always been the same for 13 and a half billion years?

[Frank Close] ...They move around, but an individual proton does not spontaneously decay and convert into something else. ...As Helen said, it's the bottom of that particular family. Other more unstable baryons can decay and come down the ladder, if you like. But nature likes to find the lowest energy state, and the proton is the lowest energy state of three quarks. And so the proton, to the best of our experiments, is absolutely stable. So the protons that were created within a second of the big bang, if you like they're all around, and they gravitationally attract one another until there's big, huge clumps of protons, which we call stars like the sun. Now, our sun is an example of a star which is dominantly made of protons and electrons. But the nuclear particles are protons. And in the heart of the sun, the protons, of course, being positively charged, like to keep away from one another. But in the heart of the sun, the temperature is of the order of 10 million degrees. And at those temperatures, the protons are sufficiently agitated that they can occasionally bump into one another. And when that happens, a series of processes takes place called fusion. ... Four protons by a series of processes come together and turn into a nucleus of helium, the next element in the periodic table. Now, a nucleus of helium is slightly lighter in mass than the four protons that made it. And that mass difference by Einstein's famous E equals M C-squared says, oh, that mass can give you energy. So the energy that the sun is radiating as light and other forms ultimately comes from the protons at its heart going through this cooking process and turning into helium.

[Melvyn Bragg] ...Simon Jolly, there are some fundamental forces in physics which I've read about from your notes. Some of them [are at] particularly play with protons. Can you tell us about that?

[Simon Jolly] The most important one that we've talked about so far is electromagnetism. So, electric charge. So we know that the proton has a positive electric charge and the electron has a negative electric charge, and it's the attraction between the two of those that holds the the atom together and then allows atoms to bond. But there are other forces at play that allow the atom itself to remain bound together. So, as Frank alluded to, when you cluster protons together in a star to try and convert hydrogen into helium, you need to overcome this electrostatic repulsion between all of these equally charged protons, there's a much stronger force, which, fortunately, we call "the strong force". So the strong nuclear force is what binds the nucleus together. Now, the third force is almost completely irrelevant to particle physicists, which is gravity. So protons have a mass, and that means that they experience gravity. In a star it is the battle between the gravitational pressure that's squeezing all of these hydrogen atoms together that gives you the energy to fuse them into helium. The fourth force is kind of a funny one. It's something that we call the "weak nuclear force". Unlike the other forces, it doesn't act at a distance. It's what we call a contact interaction. So the weak nuclear force, we only see evidence of it on a day to day basis in certain types of radioactive decay, where a neutron will decay into proton and then emit an electron and a particle that we don't see very easily, called a "neutrino". That interaction is governed by the weak nuclear force. The reason why it's important to this story is if you have four protons, that's not actually helium. Helium needs two protons and two neutrons. The energy of the gravitational compression in a star gives a proton enough energy via the weak nuclear force to convert into a neutron, which normally it wouldn't do because it's completely stable. And that gives you the strong nuclear force from the neutrons to bind those two protons into a helium atom. And the very small mass difference then gives you the heat that comes out in a star.

[Frank Close] In fact, it's the weak force Simon alludes to that is at work in that first stage in the sun's process where protons turn… into helium. And an example of how weak it is is that 5000 million years after the sun first started burning, if you were a proton in there, there's still today only a 50-50 chance that you've taken that first step in turning into helium, because the force that does it is so feeble.

[21:13]

[Melvyn Bragg] Helen Heath, we now come to gluons and pions. It's wonderful. I like the words very much indeed. Could you tell people what they, what they do, these words?

[Helen Heath] Well, gluons essentially glue the quarks together inside the proton or indeed inside the neutron.

[Melvyn Bragg] How do they do that?

[Helen Heath] Well, all our forces at the fundamental level arise because you have particles being exchanged. You think of these objects, quarks, that as far as we know, they've got no extensor. They're not touching. It's not like …they push each other by contact. So they have to interact somehow and they interact via fields. People will be familiar with fields because you can feel the magnetic field so that you don't need magnets to touch for them to move each other. So our quarks are exchanging these gluons all the time and that's responsible for the attractive force that pulls them together.

[Melvyn Bragg] Can you again answer a simple question? But can you see the gluons?

[Helen Heath] Can we see the gluons? Well, we can't see gluons directly in that we can't sort of get them out in the lab and watch a gluon propagate. What we do see is in some interactions, a gluon is produced and gluons and quarks, indeed can't get out of hadrons. Within about 10 to the -24 seconds of being expelled from a hadron, they convert themselves into more hadrons. So what we can see is the evidence of the gluon having we call fragmented, converted into hadrons. And we can look at the hadrons, it's converted into these particles with quarks in and infer the properties of the gluon from it.

[Melvyn Bragg] "See" was probably the right word, I mean, probably better word. You can measure the effect of the gluons?

[Helen Heath] You can measure the effects of the gluons. Yes, yes.

[Melvyn Bragg] What about pions?

[Helen Heath] So in order that the gluons are exchanged, the quarks have to have a charge. So forces come from charges. ... Many people are familiar with the electric charge, which is. And the electrostatic force comes from that. The charge that quarks have is something called "color". And there are three colours. The quarks have three colours and it's that charge that means that they interact via gluons. But we've never seen an object that's got overall colour out in the world. Our protons and neutrons are held together by what we've referred to as the strong nuclear force. There has to be something that's exchanged a particle that's causing that, and that particle is the pion. So the pion is a combination of either an up quark with an anti down or a down quark with an anti up or up anti up down anti down combination. So these themselves are colourless objects and their exchange between protons and neutrons is responsible for the force that holds the protons and neutrons together in the nucleus.

[Melvyn Bragg] So that's ...is also going on there?

[Helen Heath] That's also going on there, yes.

[Rather than] ...the proton being a simple single [particle], it's busy as anything.

[Helen Heath] The proton is a very, very complicated object indeed.

[Melvyn Bragg] Working its socks off. Right, Frank, why are electrons and protons so perfectly balanced as they seem to be from the very beginning, from the first nanosecond?

[Frank Close] Well, the....

[Melvyn Bragg] Oh, well, just after they started going after that, after the subatomic particles have settled a bit, then you.

[Frank Close] I mean, when you say perfectly balanced. I mean, when it comes to mass, they're very, very different. The proton is about 2000 times more heavy than the electron, but when it comes to electric charge, then they are perfectly balanced.

[Melvyn Bragg] That's what I meant. Yes. I missed that bit out.

[Frank Close] And I was sort of saying that because that is a very good question, Melvyn, and can we move on [laughter]? If I had the answer to that... But it is a very interesting question because I use this as an example of how something which is so self evident that matter is overall electrically not charged, even though there are electric charges inside atoms, the fact that electrons charges perfectly balance the protons charges is a question at the frontiers of physics, the frontiers of knowledge. And you can get right to it just from that self evident fact that it is so obvious you don't have to have higher mathematics to get to this one. It's right there staring you in the face. And it's a very profound question. And it tells us that either this is a coincidence, and as scientists, we don't like the idea of coincidences. We look for reasons.

[Melvyn Bragg] But coincidences could have rules underneath them if you dig far enough.

[Frank Close] And that's what we're trying to find. And to add to the mystery, if ... we'd asked this question 70 years ago, before the idea of quarks came along, I might have said, "Well, there's something, whatever, electric charges, I don't know. But you can add it to things or take it away from things, and so the electron has lost it and the protons got it, and that's why they balance". But now, as Helen's just told us, protons are made of quarks, and these quarks carry funny fractions of electric charge, on the average, one third of a charge. And they come together in threes, not fours or sevens or twelves, but threes. So the fact that three times one third gives you one which perfectly counterbalances the minus one of the electron is either a miracle or there's something going on. And we think, well, this is evidence that something is going on. And why it's a great puzzle is because, as we said earlier, as far as we can tell, the electron is one of the fundamental letters of nature's alphabet. And the quarks, we now see are fundamental letters of nature's alphabet. We know of nothing smaller. And yet this conspiracy of electric charges seems to say that they somehow know about each other ...

[Melvyn Bragg] [Do] you think they have many, many, many billionth sized brains of some sort.

[Frank Close] Well...

[Melvyn Bragg] ...You used the word "know" as if they know about each other.

[Frank Close] Did I use the word "no" in the sense of no or "k-n-o-w"

[Melvyn Bragg] You did know?

[Frank Close] That was a mistake, wasn't it. [laughter]...

...

[Frank Close] So this gives us a clue that somehow electrons and quarks are not completely independent at some deeper level. And whether that deeper level means ... further constituents we have yet defined. I mean, in a more profound sense, there is a theory out there waiting to be discovered which unites these different forms of matter.

[Melvyn Bragg] ...Simon Jolly how are the properties of protons applied to the treatment of some cancers, which is a developing field?

[Simon Jolly] The way that we treat cancer is largely a mixture of three modalities. So surgery, chemotherapy and radiotherapy. With radiotherapy, what you're trying to do is use x ray photons to irradiate the tumour. The way that you actually kill the cancer is you're trying to attack the DNA strands within the nucleus of a cell as it divides. So as a cell undergoes division and the DNA strands unwrap themselves, if you can break those DNA strands at that point, then the cell will fall apart and the cell division stops. If you can preferentially do that to cancer cells, then you can eradicate the cancer cells and leave the... healthy tissue spared. Well, the way that you do that with x rays is that the x ray will come into the body and occasionally it will crash into one of the electrons surrounding all of the atoms, either in the DNA strand itself, which means you lose an electron, which means the bond then breaks and that DNA strand just pops apart, or you create free radicals, so you end up with these charged ions, which a bit like "pac man" will go through and then bite and collect electrons in the nearby DNA strands. The difficulty with x rays is that, as most people know, x rays pass all the way through the body. So if they didn't, then you wouldn't be able to take an x ray of someone. But what that means is that the damage you are doing to the body happens all the way along the x ray's path. So from the entry to the exit, the key part about protons is, as Frank said, is that fundamentally, they are heavy subatomic particles compared to electrons. So if you take a proton and you accelerate it up and fire it into the body, rather than just undergoing a single interaction where it will crash into one electron and that electron pops out, the proton is charged so it's feeling the charges of all of the electrons, of all of the atomic clouds as it passes through. And it's kind of rattling as it goes ... through, a little "bump, bump, bump, bump, bump, bump" interactions. It's not losing too much energy because it's so big and it's so heavy. However, as it starts to slow down, it then deposits more and more energy. It's interacting more often with those electrons, so it's doing more damage, so it slows down more, so it does more damage, and in the end, it comes to a screeching halt and does most of its damage in the last few millimeters of its path. Now, that spike in the damage, that spike in the dose, is called the Bragg peak, after a certain William Bragg. It's the reason why we can treat cancers preferentially with protons as opposed to x rays, because we have this known range. So long as we know the energy, we know how far it's going to travel. So that means you can spare healthy tissue behind the Bragg peak and also you can do damage preferentially in the tumour rather than in front of it.

[Melvyn Bragg] Thank you very much. ...Helen Heath, particle accelerators are used to learn more about particle physics. ... What makes the proton such a good particle to accelerate?

[31:06]

[Helen Heath] There are two main advantages to the proton over, say, the electron. I mean, ideally you want a stable particle, because otherwise, when you've got a beam, they just disappear. So the two main possibilities are electron or its antiparticle, and a proton or its antiparticle. The advantages the protons have, particularly for making new discoveries... is that it's easier to get higher energy protons. And the reason for that is our discovery machines are colliders in which the particles are moving in circles. And in order to keep something moving in a circle, you are continually having to accelerate it towards the center of the circle. That's how you make it move in a circular path. And when you accelerate a charged particle, it radiates energy, and you have to replace that energy if you want your beam to keep going around with the same energy. The rate at which you radiate that energy depends on one over the mass to the fourth. And Frank already said that the electron is about 2000 times lighter than the proton. So you need 2000 squared times more energy input to keep the beams having the energy you need. And you need the energy because, as he also said, we're trying to convert the energy of the beams into the mass of new particles. So that's one advantage that protons have, you need less energy just to keep them going round. And the second advantage that they have for discoveries is because the protons are complex objects, and we're colliding pieces of the proton. We're actually having. If you think about it, we have three quarks and they have some share of the proton's energy. If they're colliding, we're actually not always colliding with exactly the same energy. So if compared with an electron-positron, where you've got the electron and positron, and all that energy is in points…so you've only got one energy, if you like, so you can only make particles of one mass, whereas the proton collisions allow us to make, have the possibility to make particles of lots of different masses.

[Melvyn Bragg] Frank, just to clear something up. Thank you very much [Helen]. When protons were created right over the Big Bang, there were also antiprotons, which were there to wipe out the protons. Why didn't they succeed?

[Frank Close] You're only asking the big questions. [laughter] That's right. As you said, the energy of the Big Bang turned into matter and antimatter, in particular, protons and antiprotons, in equal amounts, according to our best theories and observations. But today, 13.8 billion years later, matter is made of atoms containing protons, not anti atoms made of antiprotons. And the question of "so where did all the antimatter go to?" is another of the frontier questions. And again, if I had the answer to that, I wouldn't be spending my time here today. I'd be off there getting a prize for it. But it is one of the big questions…

[Melvyn Bragg] You could get a prize for explaining it! [laughter]

[Frank Close] Oh, right. Let's carry on. And it is one of the big challenges… the imbalance between matter and antimatter is as big as you can imagine. I mean, everything that we know materially in the universe is matter. There is no evidence for antimatter in bulk. We can make it, as Helen alluded to, an antiparticle at a time, and use them in experiments and control them. They're certainly there. We know their properties. We can use them to do other things. But nature in bulk does not seem to make use of them. And the cause of this imbalance, we don't know.

[Melvyn Bragg] Simon Jolly, particle physics and our understanding of the proton is founded on quantum mechanics. How firm a basis is that?

[Simon Jolly] Quantum mechanics? And I'm probably presumptuous as a particle physicist by saying this, but quantum mechanics is both the best theory that we have ever come up with and the worst. The reason I say that is that a scientific theory, really, you need two parts to it. It's trying to do two things, one of which is give you a prediction. If I know a certain set of circumstances, what is the outcome? Is the sun going to rise tomorrow? Is it going to rain? The other part is to give you some kind of insight, to understand what the process is that you're seeing in front of you, not just because we desire this intuitive understanding of nature, but also that helps us build a further picture. Okay, if the sun comes up tomorrow, is it going to be sunny or rainy? We need some information on the model that we don't yet have. The problem with quantum mechanics is it does one of those extraordinarily well, and the other one is terrible. So the predictions that you get from experiments based on quantum mechanics are some of the most accurate known to man. So the particle physics theories of interaction, so the electromagnetic interaction, the quantum theory of that interaction is called quantum electrodynamics. That is founded on quantum mechanics. Those are the most accurate scientific measurements that we have ever made. And then you have a quantum theory of the strong interaction, which is called quantum chromodynamics. The problem with quantum mechanics is the picture that it gives you is absolutely awful. It tells you that at some fundamental level, a particle is not really a particle. It's a wave. It's both here and there. It's mostly over there. It's somewhere over here. And now you have to try and conceptualize that image and go from predictions that match that picture perfectly to the solidity that we have in our day to day existence. The problem being that then if you want to make a further prediction and add further insight to the picture, how do you do it when you have no idea what's going on? I know what's going on mathematically, because I can make these wonderfully accurate predictions, but the picture is awful. And that really is one of our fundamental limitations of understanding.

[Melvyn Bragg] ...Helen Heath, the proton, it's not a fundamental particle. It's made up of smaller parts. How does that affect what happens in the accelerators?

[37:23]

[Helen Heath] Well, what happens is that you've got, as I said, you've got collisions just between parts of the proton rather than the whole proton. So you never have all the energy of the proton available. And the technical implication for that is that we can't control the energy exactly of the collision. So we actually have to throw an awful lot of protons at each other before we get the energies that we want. So that's a big technical challenge in itself, just the sheer number of collisions that you have to have in order to see something new, because most of those collisions are through very low energy parts of the proton, and they're really not very interesting from our point of view.

[Melvyn Bragg] Frank, are there any circumstances in which protons might decay?

[Frank Close] Well, ... individual protons, as in hydrogen, do not decay. That's really, I think, the background to your question. But, to clear things out, there are circumstances when protons decay in a form of radioactivity....If you've got a lot of protons together in a heavy nucleus, as Simon alluded very early on in the program, their electrical charges make them very reluctant to be there. They're trying to force each other apart. So if there are too many protons there, there's too much energy contained in that electrostatic field. And it pays for one of those protons to change into a neutron in that nucleus, and to balance the charge, it emits a positron, which is an antiparticle version of the electron. It's called a positron emitter, because by doing that, the proton has got rid of some electrical energy and turned into a neutron and changed the nucleus. So positron emitters exist. Protons can decay in certain circumstances, but protons on their own, as in hydrogen, to the best experience we have, are stable. And there is a number. We know that if the proton does decay, on the average, it's only once in about ten, with 33 zeros, of years, that's, I think, a billion, billion, billion times longer than the universe. You ask me next. I can see you coming. How do we know that? Well, it touches on this quantum...

[Melvyn Bragg] Let's swap jobs.

[Frank Close] That's right. You answer the question, Melvyn...[laughter]

[Melvyn Bragg] No no. Like the half spin that they all do.

[Frank Close] So it touches on the quantum mechanics, this thing that we do not know what an individual particle is going to do, but we know we've got enough of them that after a certain amount of time, half of them will have done something. So if we have a swimming pool full of water with billions and billions of protons in it and wait long enough, do any of them decay? And the answer is "no". So protons appear to be totally stable.

[Melvyn Bragg] You alluded there, Simon, earlier on, to questions to be asked of quantum mechanics. What are the big questions you're still looking for? I'm going to ask all three of you. So if you could be brisk, because we're near the end, unfortunately.

[Simon Jolly] Ways to break quantum mechanics would be my... and that sounds like a funny thing to say, but one of my favorite quotes is from Isaac Asimov. I think he said, the most important words in science are not "eureka" but "that's funny". [laughter] So you're always looking for things that don't fit your picture. So what we need is some information that will allow us to give more insight into the foundations of quantum mechanics, because the fundamental particle physics is built on that theory.

[Melvyn Bragg] Helen?

[Helen Heath] Well, in terms of protons, I think we're going to continue colliding at the Large Hadron Collider, and what we're hoping to see is something new coming out of that. And that would...we're not expecting the "what was that?" type moment that Simon was alluding to.

[Melvyn Bragg] And in our beginnings is our endings. Finally you, Frank?

[Frank Close] Well, obviously "something we haven't thought of" is the simple answer, but what we just mentioned, the stability of the proton. I would love to see the explanation of how it is that electrons and protons can be united together in a theoretical sense while at the same time keeping the protons stable. That appears to be the barrier.

[Melvyn Bragg] Well, thank you very much. I hope I can remember a lot of that. It was excellent. I really enjoyed that. Thanks, Frank Close, Helen Heath and Simon Jolly.

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

[41:53]

[Frank Close] I like this quantum mechanics thing. I think that we have this worry about quantum mech mechanics all wrong. We're so used to the macroscopic world, we then try to understand it in terms of quantum. I think actually it's, the quantum world is, if you like the fundamental and correct one. And when you're thinking about one atomic particle, it does all these weird things. But when you've got enough of them together, then they start doing the things that we're used to. So we are made of lots of them. And that is the key thing. You see, every time you start a game of snooker, you split the pack. If you've got one ball on one ball and you play the film backwards, you can't tell which way it's going, but you only need a couple, two or three balls in the pack, and you can tell straight away which way it's going. Things change the moment a few particles work together. I think Newton's laws are for big things with lots of particles, and they emerge out of this quantum vagueness.

[Melvyn Bragg] So you're linking the two?

[Frank Close] Yeah. I think that quantum is the way things really are and what we thought was fundamental, like Newton's laws actually emerge out of this more fundamental stuff. And we get into problems when we think that Newton is fundamental and try to understand the fundamental stuff starting from Newton.

[Simon Jolly] The thing that I am leaning towards in terms of having the picture… Frank, is right, in a sense. We are used to do day to day experience. We used to do solidity and ground and table. And these things do not fall apart in a dissolution of waves. Partly it's the fact that in order for me to understand something that I can't see at such a small scale, I need to internalize a picture of it. And the difficulty is when you take the quantum world and you're trying to … internalize the picture, you end up with this difference between the wave like behavior and the particle like behavior. And fundamentally, that may be a projection simply of the fact that we have two halves to our brain. We have the instinctive, emotional part and we have the rational, intellectual part. So we simply don't have the capacity to imagine nature in any other way. But it's the resolution of those things. If I think about electric charge; electric charge is a single discrete thing that we always find in these confined lumps. We always find it in discrete lumps.

And yet we're describing fundamental particles as being somewhere here and somewhere there. We're talking about a distribution of this… wave packet. So it's how you join those two together. Maybe the fundamental issue is that I don't have enough imagination to work out how you join those two parts. But there's always this friction between these two parts of the theory.

[Melvyn Bragg] Helen, do you want to say something?

[Helen Heath] Oh, I wanted to give you a "wow number" because it's one that always amazes me.

[Melvyn Bragg] What's that?

[Helen Heath] Well, ... we talked about the strong force holding the proton together. And so the mass of the proton is 1.6 times ten to the -27 kg. That's 1.67 divided by one with 27 zeros after it; tiny, tiny, tiny mass. And if you think about the protons pushing each other apart inside the nucleus, or indeed the up quarks pushing each other apart inside the proton, then the forces that are feeling the repulsive forces are of the order of tens of newtons. So ten newtons is the force on 1 kg from gravity. So it's just, it's a, it's a macroscopic force. It's a sort of force that you can feel. And you, you know, for carrying a kilogram around all day, you'll, you'll begin to notice it. And it's acting on these incredibly tiny particles.

[Frank Close] So the force of the whole earth acting on each of us is of the same order as the force on those two little particles.

[Melvyn Bragg] What do you make of that?

[Frank Close] It's wow. I mean, you're right. It's a wow thing. When you were saying, is it our conscious problem? I'm fascinated… If I was starting today, I don't think I'd be doing particle physics. I think I'd be fascinated by the nature of consciousness. And the question I keep thinking as a particle physicist, one atom is the same as another atom. How many of them do you have to put together before they think that they're you? Before they become self aware?

[Melvyn Bragg] When does the leap happen? ...

[Frank Close] I mean, it is clearly a number that is smaller than ten to the 34 or so, because that's what we're made of. It's clearly more than ten, but there must be some order of magnitude. I don't even know how you start addressing that question. But that was the thing that, when I read Bill Bryson's book, which was really his journey into understanding, it started off with this thing that you've got these atoms moving around, and for a brief period of about a century, they think that they are you. And that was one of those mind blowing moments, if that's the right metaphor. That moment I thought, "Wow". It suddenly hit home that it was a great one. And it's troubled me ever since.

[Simon Jolly] I suppose I would be remiss being a particle physicist and not mentioning Schroedinger's cat. Having talked about quantum mechanics...

[Frank Close] I thought you would or you wouldn't. [laughter]

[Simon Jolly] And on that note...[laughter] ...It's this story that Schroedinger said that if you take a cat and you put it in a sealed box, and then you have some radioactive source which has a 50-50 chance of decaying, and if it decays, then the cat will die. You don't know whether the cat is alive or dead until you open the box. And because it's an isolated system, then the cat is in this superposition of states, as we say in quantum mechanics. For me, the reason why he was talking about it was the ridiculousness of quantum mechanics when you apply it to the macroscopic scale. So if you take a person, a person has consciousness. We have this collection of atoms, which gives us a sense of self and awareness. So at what point does the cat not know that it's alive or dead at the same time? It's this extrapolation from the quantum world, which works perfectly on those scales to our day to day experience. ... That's the rub, as it were, between the two.

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