<u>In our Time</u> Programme 86
Nuclear Physics

Melvyn Bragg : Hello, one of the greatest scientific breakthroughs of the 20th century and certainly the most controversial was the development of nuclear physics. Harnessing the enigmatic qualities of the atom's tiny core, brought us nuclear power, and gave us the bomb, a breakthrough with such far-reaching consequences that it moved the physicist Albert Einstein to say, " Had I known I should have become a watchmaker". How can such outlandish power be released from such infinitesimal amounts of matter and what does the the science of the nucleus tell us about how our universe is built? Nuclear technology evokes strong emotional and political reactions, but what are the plain facts behind its development as a science?

With me to discuss the development of nuclear physics is Jim Alkelele, Senior Lecturer in Physics at the University of Surrey, and author of *Nucleus: A trip into the heart of matter.* Christine Sutton, Particle Physicists and lecturer in Physics at St Catherine's College Oxford, author of *Spaceship Neutrino*, and John Gribbin, visiting fellow in Astronomy at the University of Sussex and author of *Q is for Quantum* and *In Search of Schrodinger's Cat.*

John Gribbin can I begin with a brief outline of how an atom is arranged, what do we know about it's constituent parts?

John Gribbin : We know that it's mostly empty space, I think that's the most staggering thing about it. There's a very very tiny nucleus that contains virtually all of its mass, and that's surrounded by a cloud of electrons, which have very little mass indeed, with a lot a space between them, so something that seems really solid and physically sound like the table that we're sitting at, is mostly empty space, tiny particles held together by electric forces.

Melvyn Bragg : The Greek philosophers like Democritus and Epicurus talked about atoms, but they had an idea of atoms being rather like ping-pong balls?

John Gribbin : Yes they did, now that's much more like a solid object, you see they would have imagined an atom as something solid that was indestructible, couldn't be subdivided, and the great difference that the 20th century physicists brought out from the study of atoms and the study of the nucleus is this idea that it's divisible, that there are pieces within atoms that can be chipped off and broken away, and also this idea that it's far from being solid, that it is an empty space containing forces.

Melvyn Bragg : Can it...would you say that the modern interest in...or knowledge of nuclear physics could reasonably be said to have started with the British physicist JJ Thompson, in about...in the late 19th century in the 1890s.

John Gribbin : Well sitting here in London we can reasonably say that, I think there are people on the continent who would point the finger at Phillip Lenard, who did similar work at the same time. But yes, during the 1890s it was realised that pieces could be chipped off atoms, and those pieces were electrons and that's what Thompson is credited with discovering is the electron, and the astonishing discovery then when he made the announcement to the scientific community that it was possible to divide the atom, people didn't believe him. People who believed in atoms, believed that they were indestructible according to the Greek model. , and it's very hard for us to appreciate now what a dramatic breakthrough it was to find that you could knock bits off atoms.

Melvyn Bragg : From being, as it were, a Greek ping-pong ball, the atom had become....begat a different image didn't it, through Thompson?

John Gribbin : Yes, I mean the image....

Melvyn Bragg : A very Victorian image, as it were!

John Gribbin : ..it changed..it changed over the years. I mean at first people thought that it was still a kind of a solid object with the electrons embedded in it, and an a analogy that was sometimes made is like with a plumb pudding or with a raisin pudding, and that these little pieces could get knocked out, and then over a period of twenty years or so it became appreciated that as we said earlier, that there is this tiny central nucleus and the electrons outside.....

Melvyn Bragg : But let's stay with the plum pudding, which is very sort of Hobbitish and Tolkienish and so on, and very Victorian that they should (laughs)..like a plumb pudding! So that's what Thompson arrived at with the electron...

John Gribbin : Yes.

Melvyn Bragg : ..there was this spongy material and with the raisins inside.

John Gribbin : Little bits inside.

Melvyn Bragg : Christine Sutton, the plumb pudding model of the atom was turned round by Ernest Rutherford's experiments at the end of the first decade of the 20th century. Can you tell us how he approached it and how he as it were developed that?

Christine Sutton : It was something that was discovered partly through the available technology and just through pursuing curiosity. I mean Rutherford was at Manchester - he had been earlier at Cambridge when radioactivity was first discovered and radioactivity is a natural phenomenon that emits various kinds of - as we know now - bits of atoms - but of course if you didn't know that you could make bits of atoms, nobody knew that at the end of the 19th century, that that's what was going on with radioactivity and there were a particular kind of a bit of the atom that's called an alpha particle, and Rutherford really made these alpha particles his own in a sense, that as soon as he'd discovered them, he started using them as tools. So he did the exciting thing of turning the alpha particles back on the atoms.

Melvyn Bragg : What's an alpha particle?

Christine Sutton : Well we now know an alpha particle is the nucleus - the core of an atom of Helium - the lightest...the next to the lightest element of matter - Hydrogen's the lightest element. Helium's the next lightest, and this core- this nucleus, happens to be very, very stable form of nucleus that holds together and can be thrown out of heavier materials like Uranium or Thorium or these exotic things that people started using.

Melvyn Bragg : And how did he use it, how did he discover that it could be useful?

Christine Sutton : I think because he realised that he'd discovered that these were...could travel through a certain amount of matter that they had quite a lot of energy, and so it became interesting to see what happened when they went through matter, and it was in trying to look at what happened when they went through matter that he made his dramatic discoveries in Manchester.

Melvyn Bragg : But how do you see all this in 1911? I mean you've got the ....how do you....tell me how do you track an alpha particle..he knows about alpha particles, presumably he has to kind of make it up because he can't see them, but what happens next?

Christine Sutton : Yes. Well, what happens is when an alpha particle hits a material, a particular kind of material, the material will emit a little flash of light, and what these guys had to do was sit in a pitch black room with their source of alpha particles pointing at something, and then they were looking at what happened so when it went through the thing , like very thin gold foil or when it was bounced back say, so you know like hitting a tennis ball at a wall and seeing it come back and when it comes back and hits your material which is called *scintillator*, which emits the little flashes of light, you see the little flash of light, so you count it, and they were literally counting the flashes of light on their detector.

Melvyn Bragg : So..I'm sorry I'm not quite clear about this...so how did they know? They're sitting in this darkened room - Rutherford and his colleagues - how do they know this stuff's coming off as alpha particle, what's it coming off? It's coming off the...

Christine Sutton : It's coming off some kind of Radium or...

Melvyn Bragg : Yeah , but they know it's coming off...and they've got this Gold foil...

Christine Sutton : Yes.

Melvyn Bragg : Now what is - that I understand it - took them by surprise that some of the particles went right through, some of them were deflected slightly, but some ..most significantly - for this brief history - bounced straight back. Now what did that signify and why was that a surprise?

Christine Sutton : Well it was a surprise because the foil - they knew that most of the particles would go through it and that's what they expected, because the foil was very, very, very thin. I don't know if you've ever - most of us haven't actually touched Gold foil - it's a very sort of funny sticky weird stuff, course it's very, very thin, you know you're talking about something that's , you know, not many atoms thick, that the alpha particles are going through. Most of them would go through, some were slightly deflected. Now he knew that these alpha particles were really quite energetic, you know like you can imagine firing tennis balls from Pete Sampras at tissue paper hanging up, you'd expect these things just to go whacking through, and the fact that he knew that they were deflected backwards, meant that there had to be some powerful forces at work inside the atom, much more powerful than he'd imagined, and to be fair here, it took him a year or so to go away and think about what is actually happening here, and the...

Melvyn Bragg : Keep going.

Christine Sutton : ...reason why this led to the idea of a different concept of the atom was in trying to understand how these forces were at work inside the atom, because the only force that people knew about was the electric force that John mentioned earlier. So they had to understand what was going on inside the atom , in terms of the electric force there.

Melvyn Bragg : Jim Alkelele, can we...can you take up this history now? Where..so what does that signify? We're talking about 1912, and where do we go from there? What's...? Can you....summarise that stage, tells us what that signifies and then move us on from there.

Jim Alkelele : Well until then as John mentioned, there was this Thompson plumb pudding model of the atom, where it was assumed that the electrons were distributed throughout the whole space of the atom..

Melvyn Bragg : Like the raisins, plumbs.. sorry plumbs!

Jim Alkelele : ..but the alpha particles that were hitting the atoms were thousands of times more massive than the electrons, so Rutherford knew these alpha particles weren't going to bounce back after hitting the electrons. The only possible way any of the alpha particles could bounce back was if most of the mass of the atoms was concentrated in a very, very tiny volume. So he suggested that maybe the electrons which you can completely ignore in terms of the alpha particle experiment, were floating around the outside, but most of the positive charge, which he knew had to balance the negative charge of the electrons to make an atom electrically neutral, all that positive charge had to be concentrated in a very tiny volume, and that then became the atomic nucleus.

Melvyn Bragg : So he discovered the atomic nucleus?

Jim Alkelele : Yes, so his model was then the solar system model of the atom, where the nucleus was like the sun and the electron's were like the orbiting planets.

Melvyn Bragg : So what did that signify? Where did that take you physicist in terms of what this opened up as a subject, in terms of John Gribbin's idea of pure knowledge, but also in terms of what it might lead to?

Jim Alkelele : Well, we have to remember at the same time, another theory was being developed called *Quantum Theory*, which suggested that down at this very tiny length scale things behaved very , very differently, and of course when people thought about Rutherford's model of the atom, the big problem was how do these negative electrons orbit around the nucleus without being sucked in due to the attractive positive force.

Melvyn Bragg : Yes, so the nucleus is positive and they're negative, they supposed to attract...

Jim Alkelele : ...then they should....

Melvyn Bragg : ..and therefore it should collapse in....

Jim Alkelele : ...they should spiral in...

Melvyn Bragg : ...I remembered that much from 4th form physics!

Jim Alkelele : ..very, very quickly, yes.

Melvyn Bragg : They didn't.

Jim Alkelele : They didn't.

Melvyn Bragg : So why didn't they?

Jim Alkelele : Well, at this point the Danish physicist Niels Bohr came in. He'd gone to work with Rutherford. He was interested in Rutherford's model of the atom, and he applied the then very new rules of Quantum Theory to show how an atom could remain stable. So he suggest that these electrons followed fixed orbits around the atom, there were certain quantum rules that stopped them from jumping...from spiralling into the atom.
They would only change from one orbit to the other according to certain very strict quantum rules, and so he gave atoms stability.

Melvyn Bragg : What I'm really fascinated by - it comes back to John Gribbin's remark at the very top of the programme about the development of this subject being associated with the development of technology. How did they find out about this? How did they track it? How did they see? What instruments are they using for measurement?

Jim Alkelele : Well, the...

Melvyn Bragg : I mean we're talking about you know, the beginning of the 20th century - the first 2 or 3 decades.

Jim Alkelele : It was very, very crude experiments, as Christine mentioned they had to sit in darkened rooms for hours upon hours, getting their eyes adjusted to the dark, just to see the tiny flashes of light on scintillation screens. They developed special counters - Geiger counters - which would give off a click every time a sub-atomic particle, like an alpha particle entered in them. But a lot of these ideas were theoretical ideas, that they knew and atom had to be stable - atoms exist - and if atoms had this structure of electrons orbiting around the nucleus, there had to be certain rules that allowed them to be stable.

Melvyn Bragg : I mean we're talking about imagination anyway aren't we?

Jim Alkelele : Absolutely, yes, yes.

Melvyn Bragg : Imagination, illustrating our imagination...

Jim Alkelele : Yes.

Melvyn Bragg : ...and all the models that John said in one of his articles, about these models and ideas and analogies that we have which are very useful, but **never can be accurate**.

Jim Alkelele : Yes. Well of course the other thing is, that because the atom and its nucleus are subject to the rules of quantum mechanics, these are very, very strange concepts and we can't picture...I mean we learn at school that the atom is this nucleus with electrons buzzing round the outside, but of course that's not an accurate picture of what an atom is really like. We can't imagine what an atom is really like, because it's something so far from our every day experience, and so we can really only describe it using mathematics. All physicists have pictures of what things look like.

Melvyn Bragg : Can I move on to talk about, or can *you* move on (laughs) to talk about the power of fission here? Jim Alkelele, Iron is the most stable nucleus of all, I've read, of all the elements, with a total of 56 protons and neutrons. That seems to be very significant Iron56, can you tell us why that's significant in this story of nuclear fission.

Jim Alkelele : Well, protons and neutrons are the two types of particles that make up a nucleus, and protons are positively charged, neutrons are neutral, so they don't attract each other by electrical forces, they attract each other by the strong nuclear force, the force that only acts within the confines of the nucleus, and so a strong enough nuclear force will hold the protons and neutrons together, but if you get a nucleus that's too big, then protons on either side of the nucleus will only feel their mutual repulsive electrical force, because the strong nuclear force has the property that it only acts over a very short range, not even across the whole span of a large nucleus.

Melvyn Bragg : So the strong nuclear force is really...this nuclear strong force is really a law to itself so far isn't it?

Jim Alkelele : It's one of the four fundamental forces.

Melvyn Bragg : Well, where does Iron come in? Iron's supposed to come in significantly, and I haven't got there yet.

Jim Alkelele : Well, Iron happens to have a certain structure. Protons and neutrons hold together according to certain rules. People developed models of the nucleus. For instance one of the early models was the liquid drop model where a nucleus was likened to a drop of water, the way it wobbles about. Later they developed the idea that protons and neutrons follow the same rules that electrons follow in the way they arrange themselves in orbits and shells around in the atom. Protons and neutrons also seem to fit together in shells within the nucleus, and so you have to understand how these shells get filled up according to certain quantum rules, to explain why it is that Iron with a certain number of protons and neutrons happens to have just the right arrangement to make the most of the strong nuclear force that holds them together.

John Gribbin : But something has to Jim.

Jim Alkelele : Absolutely.

John Gribbin : I mean it doesn't really matter that it's iron or what the rules are, you've got a trade off between one force that's trying to hold things together...

Jim Alkelele : Yes.

John Gribbin : ...and the electric force that's trying to blow things apart, and if you put enough particles together, if it's big - the electric force is going to win, if it's small - the strong force is going to win , and Iron is just in the middle, and so something has to be in the middle and it happens to be Iron.

Christine Sutton : But it wins better, Iron wins better than a small nucleus......

John Gribbin : Yeah.

Christine Sutton : ...like Carbon say, because in Carbon a lot of the protons are near the surface of the nucleus, so they don't have other things trying to hold them in. So as John said, it is a trade off, but you can imagine it almost like a valley, where you have a sort of stable bottom with a deepest point in that valley, which is where Iron is, the most stable thing, and all the other nuclei that we know about are like on the hills of the valley and they're all wanting to sort of tumble down into that most stable point.

Melvyn Bragg : John Gribbin, nuclear fission was discovered in the 1930s, how did scientists get nuclei to split and what happened when they did?

John Gribbin : It's really, it's a development of the original thing that Rutherford and his colleagues were doing firing alpha particles at atoms and Gold foil to see what happened, and as the technology improved and it became possible to accelerate these particles more effectively, bombard other nuclei more effectively and you had better detectors to measure what was going on, people did more and more experiments until they reached a point where they were firing particles at nuclei, at targets, and what was coming out wasn't those same particles being bounced off or reflected, they were getting debris from smashing apart the particles were colliding with, that's technology again, more energy going in, so you're able to do more interesting things.

Melvyn Bragg : So what did that result in? What happened? Okay in the 1930s, they could split the nuclei, so that meant what?

John Gribbin : Well it meant that the nucleus itself is indivisible. Now we've gone from the stage at the end of the 19th century...

Christine Sutton : *Is* divisible.

John Gribbin : ....*is* divisible , sorry, that at the end of the 19th century, that this sort of shattering revelation that the atom is divisible, and then you have the idea that there's a solid nucleus inside the atom, and at first that was then thought of as being a fundamental entity that couldn't be divided. Now you've reached the stage where you're dividing even the nucleus up into pieces, and that tells you in terms of pure knowledge, you know, you can study the pieces and find out how they join together, and then eventually learn how to make use of the energy that's released, but again it's a great conceptual advance, you know where does this process stop?
Does matter carry on being divided for ever and ever, so people were absolutely fascinated by the discovery.

Melvyn Bragg : Christine Sutton, why is Uranium always used in nuclear fission?

Christine Sutton : Well the big thing that...with fission is that we talk about actually breaking a big nucleus up into two smaller lumps, you know just two lumps, and that goes back to my sort of valley analogy, that Uranium is at one end of this valley, sort of near the beginning of the valley, where the walls are steep, and that's the heavy Uranium nucleus, when you break it up into two fragments, they're lower down in the bottom of the valley, by releasing...going down to the bottom of the valley you've released a lot of energy - that's one reason why you use Uranium. The other reason why you use Uranium is that in fact to trigger fission, you don't use alpha particles as John mentioned, you use these neutrons- the things that have no electric charge, and are actually rather tricky to handle, but the neutrons, because they have no electric charge, they can sort of infiltrate into a nucleus, there's nothing to sort of repel them and say "go away" you know, "you can't come in here". The neutrons just sort of creep in like invisible secret agents or something, and the addition of neutron upsets that delicate balance between these strong forces and electric forces that we've talked about.

The whole thing about nuclear physics is this competition that's going on between the electric forces that we are familiar with - more familiar with, and the strong forces that even the physicists sort of, feel a bit uncertain about. In Uranium, once this little neutron comes in it can easily trigger the fission reaction and release the energy that we've talked about.

Melvyn Bragg : The power of nuclear fission comes from a chain reaction as I understand it, which releases energy trapped in the nuclei, how is that chain reaction set off?

Jim Alkelele : Well what happens when a Uranium nucleus breaks in two by absorbing a neutron, is that it also releases several neutrons from within it, that existed within it in the first place. Those neutrons then fly off, and if one or more of those is captured by a surrounding Uranium nucleus, they might prompt that to undergo fission as well, and so all the time a neutron causing one Uranium nucleus to fission, allows another neutron coming out to cause another Uranium to fission, you'll get a chain ....a sustained chain reaction. If more than one of the neutrons in a Uranium nucleus causes fission, then you get a run away chain reaction, where more and more...exponentially more and more Uranium nuclei will fission, and that's of course what you get in a bomb.

Melvyn Bragg : Where does this....Christine Sutton, where does this trapped energy come from?

Christine Sutton : That's the hard question I was hoping nobody was going to answer...ask!
No, I mean I think the simplest way of thinking about this is that if you broke a Uranium nucleus up into all its 296..8..whatever neutrons and protons, individual pieces, and you weighed each of the protons and neutrons, you'd get a total mass for all the building bricks. But when you weigh...find out the mass of a Uranium nucleus, **that mass is different from all those bits added together**, and we know from Einstein's theory that mass and energy have an equivalence, E=Mc^2, the only equation in physics that any of us have heard anything about. So E -energy, Mc^2 - the mass, when you...when the Uranium breaks up, it's mass is changing and that changing mass comes out as the energy.

John Gribbin : It's energy locked up holding the Uranium together....

Christine Sutton : Yes, yes.

John Gribbin : ..but because the Uranium is unstable it very much would prefer to break up into two more stable pieces and give off this extra...

Christine Sutton : So going back tot he valley analogy - you know, we know about hydro electric power, if water runs down a valley - you get energy coming out, because the water's changed its position in the valley....

John Gribbin : Uranium is higher..

Christine Sutton : ..Uranium has changed its position and is releasing energy. But it is related to the mass difference as well.

John Gribbin : Yes.

Melvyn Bragg : In fusion, the nucleus of one atoms is fused to another, as I understand it, and energy is released. Under what circumstances can you nuclei be forced to fuse, be made to fuse?

Christine Sutton : Under what circumstances can they be made to fuse? Well in that case, what we're trying to do is to bring - remember now, nuclei have positive charges on them - they have to overcome that natural repulsion there is - you know likes repel , unlikes attract - so you can either have sort of very sort of energetic nuclei that come together with quite a lot of energy, so that the energy that they have overcomes the natural repulsion.

As long as they can get close together, the strong force that Jim introduced, he mentioned that the strong force is very short range. If you can get the nuclei close enough together so that that short range force locks in - you know it's a bit like Velcro - imagine you know, most of the time when your garments with Velcro on like your waterproofs, Velcro is far apart, there's no problem, but you just get it to touch slightly and kmmp it snaps in, well the strong force is a bit like that, and if you can get that to happen, with these nuclei which are light weight. Of course now we're talking about going the other side of Iron, we're talking about light weight nuclei that want to get to this bottom of the valley, and the way they do that is by joining together, and again it has to do with this competition of forces.

Melvyn Bragg : How do they do that? How do you manage to do that Jim?

Jim Alkelele : Well it happens around us, this is the reason why the sun shines, what's going on inside the sun is a thermonuclear reaction, so you have light element Hydrogen or protons which are the nuclei of Hydrogen, fusing together to make heavier nuclei. First of all they make heavy Hydrogen, Deuterium and then Deuterium fuse together to make Helium and so on, this is how the elements - the very light elements are produced inside stars. What we'd want to do is try and mimic that reaction in the laboratory on Earth, but what we don't have are the conditions in the centre of the sun, a hundred million degrees centigrade, and we'd like to have those conditions in the laboratory because that's the temperature, the energy that we need to push these things close enough together in the first place.

Melvyn Bragg : What are the...what are the benefits of nuclear fusion going to be. I mean at the moment what you're saying is we can't do it well enough.

Jim Alkelele : We're working on it, but then people working on nuclear fusion have been saying that for a very long time (Christine giggles)! But if and when they succeed, it has several benefits over nuclear fission, which is the way that we produce nuclear power at the moment. First of all it produces more energy, secondly we don't have to rely on a limited supply of Uranium, we can make use of water hopefully, sea water, which is unlimited pretty much, and thirdly it has the benefit, in fact that it does have....it's a cleaner form or energy, it doesn't have the radioactive waste of the level of nuclear fission.

Melvyn Bragg : But there are no nuclear fusion reactors at work in the world at the moment are there?

Jim Alkelele : Not yet. People working in the field have said for many years now that nuclear fusion is about 40 years away (Christine giggles) ....

John Gribbin : They've been saying that for at least 40 years!

Jim Alkelele : ...they keep saying...they've been saying that for forty years. They say now it's forty years away, but what's different now is they feel they have a road map, they know exactly what they should have achieved, 10 years from now, 20 years from now.

John Gribbin : People have actually achieved fusion, but it takes more energy to make things fuse together at the moment, than you get out from the reaction, so it's not a very efficient....

Jim Alkelele : I think they've just about gone beyond the break even...

John Gribbin : ..just about break even.

Melvyn Bragg : D'you think Einstein - we've only got a few minutes left -d'you think Einstein was right - that he'd have been better off being a watchmaker and his whole adventure in nuclear physics hadn't started?

John Gribbin : Oh absolutely not, I mean for two reasons, I mean someone else would have done it, but I think the benefits do outweigh the costs, we've managed to avoid nuclear war and we've got a lot of benefit out of this stuff...

Melvyn Bragg : Such as? Can you instance a few..?

John Gribbin : ...well I think nuclear power though that's an emotive subject. I think in the long term we will have clean fusion power and it will be good for society and the benefits from medicine. People very seldom appreciate how much benefit comes from radioactivity in medicine.

Melvyn Bragg : Can you give us some examples?

John Gribbin : Well dealing with tumours, cancer and so on, radiation therapy, things like the imaging that's done to look inside the body without invasive surgery, all of that comes from nuclear physics. Magnetic resonance imaging MRI used to be called *nuclear* magnetic resonance - because it's a nuclear physics concept. But people dropped the word nuclear because they saw it had these negative conurtations, but of course that's all nuclear physics.

Christine Sutton : I think the other thing is that it has helped us to understand the universe and we are...describe ourselves as *carbon-based life forms* - the carbon that's in all of us, was created originally in the heart of a star, and I think that's a very sort of powerful concept and something that only became...we became aware of in the 20th century with nuclear physics.

Melvyn Bragg : So it's this way, we can go back to the idea of origins can we John Gribbin?

John Gribbin : Absolutely, I mean this is very much my own pet area of interest - the relationship between ourselves humankind and the universe at large, and that we are products of the stars, we are absolutely literally stardust.

Melvyn Bragg : I can't think of anything to say after that. To tell you the truth I feel quite exhausted (laughter) having concentrated on that for 3/4 of an hour. Anyway thank you all very much John Gribbin, thanks Jim Alkelele, thank you to Christine Sutton. Next week we're taking on the medieval heresy of the Cathars.