

Note Numbers in Red Correspond to PowerPoint Slides

1THE GOD PARTICLE

By

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2INTRODUCTION

As most of you will know, the so called “God Particle” finally moved from the realm of theory to actuality when its existence was verified by a team working at the Large Hadron Collider (LHC) - that’s a fancy name for a very expensive machine which smashes sub-atomic particles together - in Geneva in 2012. This generated a huge amount of publicity at the time, and the LHC as it restarts and indeed the whole field of particle physics is generating a lot of publicity this year, and I thought you might all like to hear about what this all means and why the God Particle was christened with such a surprising name.

Actually the LHC is a story in itself, an exquisite machine that tells us about the phases of the moon, the water level in Lake Geneva and the time the TGV leaves for Paris – but I’m not going to focus on that or the technicalities of the LHC today. I think it’s going to be an interesting day in which most of you will learn lot’s of new and surprising things.

Well I think the media picked up the “God Particle” name from the **3**title of Leon Lederman’s popular book on the topic which was first published in 1993, although initially he wanted to call the book *The Goddamn Particle* rather than *The God Particle* because it was so hard to find. Actually, most scientists dislike the name “the God Particle” – Lederman said it only offended two groups of people, those who believed in God and those who didn’t! But, in some ways it does have a meaning way beyond what Lederman intended, as I hope to explain later. Apart from anything else, if it wasn’t for this particle, the universe as we know it couldn’t exist, it would just be a mess of massless particles flying around at the speed of light.

4The so called God Particle, which scientists prefer to call the Higgs boson, is important because it completes what is called the Standard Model of Particle Physics – the model which explains how all the particles which make up our material world, and the forces which operate within it, fit together. As I imagine most of you don’t have a good knowledge of particle physics I’m going to start much nearer the beginning of the story. Of course, this is a very large and difficult

subject; I could lecture on it every day for months without getting to the end of it, so today we're just going to take a very basic look at some of the important parts. I warn you in advance that I'm going to be missing out lots of things and at times what I'm going to say will lack complete academic rigour – but, it will be correct insofar as it goes, even if I don't always explain why, and I think that by the end of the day you'll have a good overview of this field. I think it will be most helpful if we approach this subject historically, so we're going to start with some historical background.

HISTORICAL BACKGROUND

5 Atomic Theory

The idea that matter was divided into tiny pieces – atoms – has been around for millennia. The idea was perhaps most developed by the ancient Greeks as early as the 6th century BC. However, their thoughts were based purely on philosophy, and there was no evidence to support the idea and indeed there was little or no development of the idea until the beginning of the 19th century.

6Modern atomic theory began with an English scientist, John Dalton, in 1805. He proposed that each element consists of atoms of a single, unique type, and that these atoms can join together to form chemical **7**compounds. So, elements are single substances like hydrogen, or oxygen and iron and these can join together to form chemical compounds. For example, two atoms of hydrogen can join with one atom of oxygen to form a molecule of water. Currently we know of **8**118 elements of which 90 exist naturally (the others are unstable and decay into other elements). Most of the 90 natural elements exist on earth combined with other elements in the molecules of chemical compounds. Some are common like carbon, oxygen and iron. Some are incredibly rare, for example, it's estimated that there is less than an ounce of astatine in the whole of the earth's crust.

Dalton's atomic hypothesis did not specify the size of atoms. Common sense indicated they must be very small, but nobody knew **9**how small. Therefore it was a major landmark when in 1865 Johann Josef Loschmidt measured the size of the molecules that make up air. An additional line of reasoning in support of particle theory (and by

10extension atomic theory) began in 1827 when botanist Robert Brown used a microscope to look at dust grains floating in water and 11discovered that they moved about erratically – a phenomenon that became known as “Brownian motion”. J. Desaulx suggested in 1877 that the phenomenon was caused by the thermal motion of water 12molecules, and in 1905 Albert Einstein produced the first mathematical analysis of the motion – Einstein’s first great contribution to science. French physicist Jean Perrin used Einstein’s work to experimentally determine the mass and dimensions of atoms, thereby conclusively verifying Dalton’s atomic theory.

Atoms are incredibly small – a full stop on a page of my notes would contain around one hundred billion carbon atoms and you breath in some million, billion, billion atoms of oxygen every time you breathe. That’s incredibly small, you’d have to magnify the full stop in my notes to 100 metres across to enable you to see the atoms in it with the naked eye. But atoms aren’t the smallest particles of matter. As we’re about to see, the idea that the atom was the smallest particle of matter had already been demolished by Einstein’s day, through the discoveries of a great English physicist – J J Thompson.

Sub-Atomic Particles

13Until 1897 everyone, or almost everyone, had thought that atoms were the smallest particles of matter, but in that year J J Thompson 14discovered the electron through his work on cathode rays (electrons were initially called cathode rays because no one knew what they were). Most of you will remember that the original televisions used large cathode ray tubes to project the image. Thomson established that electrons were very light and small and had a negative electric charge. In 1903 he postulated that these electrons were distributed throughout the atom, possibly rotating in rings, with their charge balanced by the presence of a uniform sea of positive charge. This 15later became known as the ‘plum pudding model’, although we now know that nature didn’t order that dish – the atom isn’t like that.

At the end of the 19th century physicists thought that they knew almost everything and there wasn’t much more to discover. How 16wrong they were. As Niels Bohr said “prediction is difficult, especially when it’s about the future”. Even in the field of atomic

structure, we just didn't realise how complicated things were, and indeed we didn't even begin to comprehend the whole picture until the early 1970's when the Standard Model was theoretically completed following the postulation of the Higgs boson in 1964 and the unification of three of the four forces with quantum theory.

17 Actually, the Higgs boson should be called the EBH boson (adding in the names of Engelert and Brout who first postulated it and beat Higgs into print by seven weeks). So, Peter Higgs in England was the last person to come up with this idea – but, initially at least, Higgs got all the credit, the particle is named after him and he was named first (along with Engelert, Brout had died in 2011) in the awarding of the 2013 Nobel prize. Indeed there were other scientists who published additional parts of the idea (although a little later) and rarely get any credit at all, like Gerald Guralnik, Carl Hagen and Tom Kibble.

Even now there are enormous gaps in our understanding of particle physics, and indeed our understanding could be completely mistaken as we shall see later.

Returning to the beginning of the 20th century, in 1908, the great New Zealand born English scientist Ernest Rutherford and his team, established that positively charged entities which he called Alpha rays **18** (these were actually helium nuclei stripped of their electrons so as to be positively charged) were deflected on their passage through thin gold foil in a way that could not be explained on the “plum pudding” model of the atom. These Alpha particles either passed straight through the foil with very little deflection, or were deflected by one or two degrees, but a small minority were deflected through large angles. He then discovered that some were bounced backwards. That was incredibly surprising at the time, it was as if you fired an 18 inch shell at your garden fence and saw it bounce back.

20 In 1910 Rutherford proposed that the atom consisted of a tiny positively charged central core or nucleus comprising virtually all the mass of the atom, with negatively charged electrons surrounding it – so that the atom was electrically neutral. Most Alpha particles would pass straight through Rutherford's atom because they were too far away from the nucleus. A very few would have close encounters with the nucleus and be deflected through large angles. An even smaller

number would encounter the nucleus head on and bounce back. Rutherford announced his final atomic model in 1911. The nucleus of an atom is incredibly small. Going back to the illustration of the full stop in my notes, you'd have to magnify this to the size of the earth to enable you to see the atomic nucleus.

Rutherford's model had a fatal flaw, it would be unstable. Even if the electrons orbited around the nucleus the atom would collapse, because the electrons would continuously lose energy as they orbited and quickly fall into the nucleus.

21 Around the same time, another English scientist Frederick Soddy showed that elements existed in different forms as regards their atomic weight, but with identical chemical properties. We now know that the chemical properties depend on the electrons and only on the electrons. That's because atoms interact with each other on the basis of the interaction of their outermost layers – the outer shell of electrons. This is an interesting subject, but because of time constraints we're not going to look at that aspect of things at all today.

A little later, a Danish scientist, Niels Bohr, working with Rutherford, had the crucial insight that what mattered was the electric charge on the nucleus and that this was equal and opposite to the number of electrons in orbit around the nucleus. This enabled Bohr to correctly identify radioactivity (discovered by Madame Curie) as a nuclear and not an atomic phenomenon and to identify nuclear charge as the essential quantity. But, Rutherford wouldn't listen to Bohr and prevented him from publishing his ideas, so Soddy and others got the credit.

Bohr continued working on another problem, the instability of Rutherford's atom. To do this he turned to the concept of the **22** quantum discovered by Max Planck in 1900. The idea of the quantum is that energy (and other things like mass, time and space) don't exist in infinitely divisible quantities but have a smallest possible unit. He theorised that electrons circulated around a small **23** positively charged nucleus, but that they could not be in absolutely any orbit around the nucleus, rather only those orbitals where the **24** energy of the electrons in those orbitals corresponded to multiples of the quantum energy. Things go in discrete steps like a staircase.

He supposed that in these states the electron did not emit radiation, because it couldn't do it gradually, and so the electrons could orbit the nucleus indefinitely. He turned out to be correct, so the instability problem was solved and the science of quantum mechanics was born. It's rather like when you're on a ladder or a flight of steps, you can only stand on one step or another and not in-between the steps.

Bohr also realised that the frequency of light emitted or absorbed by atoms was dependent on the energy change involved in electrons moving from one permitted orbit to another. When an atom is exposed to light the electrons can jump up to a higher orbit by absorbing energy from the light. When the electron jumps back down it emits the energy it originally absorbed and now loses as light. It's rather as if you jumped up from the floor to a bench. You would have to expend energy to do that and when you jumped back down you would regain the energy and have to absorb it in your feet and legs.

Bohr published these ideas in a set of papers he sent to Rutherford in March 1913. Initially Bohr met with great resistance as his model was contrary to many of the principles of classical physics – but it did correctly predict the size of simple atoms and the frequencies of light they emitted.

25 About the same time another member of Rutherford's group, Henry Moseley, had confirmed the idea that the positive charge on the nucleus of an atom was a unique whole number for each element and was the key factor that determined its position in the periodic table of the elements. Experiments soon showed that Bohr's atomic model gave the correct results for the frequencies of light (or actually X-rays which are the same as light but of a much shorter frequency and higher energy) emitted by various elements when they were bombarded with electrons.

Bohr's simple model with circular orbits for electrons was developed **26** by another theoretical physicist Arnold Sommerfeld who showed that electron orbits were actually elliptical – which explained certain **27** observations about the light emitted from atoms which had puzzled Bohr. So the atom was finally characterised as a positively charged nucleus with a number of electrons (equal in number to the positive charge on the nucleus) in a variety of orbits around the nucleus.

28But, what were the positively charged particles in the atomic nucleus? In 1920 Rutherford had given the name proton to the particle making up the nucleus of a hydrogen atom which he had shown to be the lightest possible nucleus. He also conceived the possibility that the nucleus contained non-electrically charged particles which he called neutrons.

Well he was right, although the neutron wasn't finally discovered until 1932. Its existence explains why there are different kinds of atoms of many elements – their nuclei contain different numbers of neutrons but the same number of protons. So, for example, there are **29**two different kinds of carbon – carbon 12 and carbon 14. Carbon 12 has 6 neutrons and 6 protons in its nucleus, whereas carbon 14 has 6 protons and 8 neutrons. Carbon 14 is unstable and gradually decays and that's the basis for so-called carbon dating. Of course, both kinds of carbon have the same number of electrons, because the number of electrons equals the number of protons. That's why both kinds of carbon are chemically the same, because the chemical properties of atoms depend on the electrons as we've already said.

30So to sum up atoms are positively charged nuclei made up of positively charged protons and electrically neutral neutrons with electrons, equal in number to the protons in the nucleus, in various orbitals around the nucleus. That makes the atom in its normal state electrically neutral. The chemical properties of the atom depend on the electrons and not at all on the nucleus, but the radioactive properties of the nucleus depend largely on the number of neutrons in it – because neutrons are able to decay as we shall see later.

Atoms are mostly empty space. You think this desk is solid, but it's actually mostly empty space. If the nucleus of a hydrogen atom was one centimetre across the electron in orbit around it would be half a kilometre away. All the rest would be empty space, there's relatively much more empty space in an atom than between the planets in the solar system. But the forces within the atom holding it together, mainly the electromagnetic force between the electrons and the positively charged nucleus, make it appear solid. That's why you don't fall through your chairs and sink through the floor.

Originally scientists thought that electrons and protons were like tiny billiard balls, but they were quickly finding out that they weren't like that at all.

The Nature of Sub-atomic Particles

In 1914 Einstein realised that the mechanism for atoms emitting light as electrons changed orbitals combined with the evidence from the **31** photoelectric effect verified his earlier 1905 proposal that light could be 'quantised' into particles – although most people still didn't accept that, because they believed in the wave theory of light. In **32** 1922 an American physicist, Arthur Compton, finally proved that light could indeed be quantised by his measurements of what happened when X-Rays were scattered by graphite – work for which he got the Nobel Prize in 1927. By then Einstein's quantum of light had been christened as the photon and it had been accepted that there were two theories of light – the wave theory and the particle theory – so that light had a dual character.

33 About this time a French scientist Louis de Broglie theorised that this dual wave particle nature applied to all matter not just light. We **34** now know that he was right, matter particles like electrons can indeed be diffracted as if they were waves. That's going to be an important concept for us later – so just keep it in the backs of your minds. At around the same time an Austrian physicist, Wolfgang **35** Pauli, showed that there were strict limits on how many electrons could occupy each orbital, or energy level, around an atom. This was his famous exclusion principle, that no two electrons in a particular atom can have precisely the same quantum state.

36 Returning to the wave idea Max Born and other physicists quickly realised that this representation of a particle as a wave meant that we could not know exactly where it was until we measure that – indeed it's probably meaningless to ask the question without making a **37** measurement. Lots of modern electronics – like tunnel diodes, of which there will be many in your mobile phones, depend on that principle. Worse than that, whether the 'thing' we observe seems to be a particle or a wave, depends on the kind of measurement we **38** make. Further, as Heisenberg showed, theory requires we can never know exactly where it is and precisely how it is moving at the

same time. That's called the "uncertainty principle" and it's not just a problem of measurement, the fact that we disturb things when we measure them. It's a real theoretical limit the universe imposes, it's a consequence of wave particle duality. This fusion of ideas in quantum physics has become known as the "Copenhagen interpretation" of quantum mechanics.

To sum up, what we call sub-atomic particles, like electrons and protons, behave like both particles and waves. Sometimes like one and sometimes like the other depending on what and how we measure.

39This wave particle duality leads to really weird behaviour. If we send light through two slits [diagram] we get a pattern of light and dark interference fringes on a screen behind the slits. That's because the light waves passing through the two slits inter-react. In some places they reinforce each other and we get a bright streak and in other places they almost cancel out giving a dark streak. Well we get **40**the same result if we send a beam of electrons instead of light, [diagram] because the electrons display their wave like qualities.

That's straightforward, but now let's come on to strange things. We get the same results if we send the electrons one at a time – it's as if each single electron somehow went through both slits. That's weird.

41But even stranger, if we install a detector after the two slits, so that we can detect which slit the electron went through [diagram], the interference pattern disappears. It's as if the electron knows it's being watched. That's what I meant when I said earlier that whether a particle behaves like a particle or a wave depends on what we measure and how we measure it.

42Moving on, as a physicist called Paul Dirac (who later fascinated Peter Higgs) predicted, most particles have a corresponding anti-particle which carries the opposite electrical charge. So there is an anti-electron which carries a positive charge and an anti-proton which carries a negative charge. In our universe these kinds of particles don't exist naturally because they annihilate themselves when they encounter their normal counterparts in an explosion which releases lots of energy in the form of photons. Anti particles are important though and we'll be coming back to them later.

Looking further ahead physicists didn't realise how to combine quantum theory with electromagnetism until just after the Second **43**World War when Richard Feynman and Julian Schwinger worked out what came to be called quantum electrodynamics. Actually it had already been worked out during the war by a Japanese physicist, but the news never reached the West until later. This theory combined the electromagnetic force – carried as we've already seen by the photon – with electrons and protons and showed how they interacted.

It then took another quarter of a century to extend quantum theory to cover the strong and weak nuclear forces – but we'll come back to that later. We've never managed to unify quantum theory with the gravitational force, and again we'll return to that later.

Further Development

The simple model we've been looking at so far of atoms made up of a small nucleus composed of neutrons and protons with electrons in orbit around the nucleus soon became more complicated.

In 1931 Wolfgang Pauli proposed the existence of a new matter particle called the neutrino to conserve energy, momentum and spin in some nuclear decay reactions. Neutrinos are very small and carry no electrical charge and almost never interact with ordinary matter – they could fly through millions of kilometres of solid lead without interacting with it.. We now know that neutrinos have a mass, but a very small one which has not yet been accurately measured.

Neutrinos are incredibly common and are emitted in many nuclear processes. They're so common that if I hold this 10 cm square piece of paper directly towards the sun around 6.5 trillion neutrinos will pass through it every second, and it won't matter whether I can see the sun or not because neutrinos almost always pass straight through matter without interacting with it. Indeed we ourselves are radioactive, we emit around 400 neutrinos a second, mainly as a result of the radioactive decay of potassium in our bones.

We now know that neutrinos exist in three distinct types – electron, muon and tau neutrinos.

44In the late 1960's Abdus Salam, Sheldon Glashow and Steven Weinberg showed how nuclear decay occurred and how this

integrated with electromagnetism. Because nuclear decay is controlled by the weak nuclear force this integration was called electro-weak theory. This weak nuclear force is carried by three new force particles called W^+ , W^- and Z gauge bosons. These are very heavy particles and so the weak nuclear force only acts over very short distances. This theory was verified by the confirmation of the existence of W and Z particles at CERN's predecessor to the LHC (LEP) in 1983. In fact the huge masses of the bosons carrying the strong nuclear force absolutely requires the existence of the Higgs boson because they are gauge bosons and should be symmetrical with the other gauge bosons, the photon and the gluon. That is they should have no mass at all. The Higgs field was responsible for breaking the symmetry between the gauge bosons in a process called spontaneous symmetry breaking. A concept we'll return to in a minute.

45In 1964 Murray Gell-Man and George Zweig had proposed that protons and neutrons were made up of smaller particles which they called quarks. The quarks are held together by the strong nuclear force which is carried by another kind of gauge boson, interestingly called a gluon. This force is about 137 times stronger than the electromagnetic force and a thousand billion times stronger than the weak nuclear force. In fact there are six different kinds of quarks. Protons and neutrons are each made up of three quarks bound together. Experimental evidence of the existence of quarks was developed through electron - proton collisions at the Stanford Linear Accelerator in 1973.

These developments depended heavily on the idea of the Higgs field which solved a number of problems, the mass problem we've just mentioned and also infinities arising in the equations, which would otherwise have existed. As I've already said, no one has ever managed to integrate gravity with nuclear forces.

Having looked at a very brief overview of the historical development, I think it's now time to move to the present day and start to think about the Standard Model of Particle Physics which seeks to bring everything together.

THE STANDARD MODEL OF PARTICLE PHYSICS

In the standard model we have matter particles and force particles which convey the various forces of nature. Matter particles are called fermions and force particles are called bosons.

46 Fermions consist of two kinds of particles, hadrons which are made up of quarks and leptons which are not made up of anything smaller.

47 In hadrons we have particles like the proton and the neutron which are each made up of three kinds of quarks and mesons which are made up of two quarks, actually a quark and an anti-quark.

Bosons exist in six different kinds; the photon which carries the electromagnetic force, W^+ , W^- and Z bosons which carry the weak nuclear force and control radioactive decay, gluons which carry the strong nuclear force and hold quarks together, the hypothetical graviton which (if it exists) carries the gravitational force and the Higg's boson – the God Particle – which prompted our talk today. You'll remember the wave particle duality we looked at earlier, that's why there are particles which carry forces like the electromagnetic force that we usually think of as waves in everyday life. The strong nuclear force is very unusual; it's like an elastic band. When quarks are close together the force weakens, but as you try and pull them apart it strengthens. That's why hadrons and the nucleus of the atom are so stable. However, you will appreciate that the protons in the nucleus are all positively charged and so electrically repel each other. Thus there are two opposing forces – the electromagnetic force trying to push the protons apart and the strong nuclear force trying to hold them together.

Eventually, as you add more and more protons into the nucleus, the electrical disruption can overcome the attraction of the strong nuclear force. That's why uranium with 92 protons in the nucleus is the heaviest naturally occurring element. Neutrons, of course, have no electrical repulsion as they have no electrical charge, but they are still involved with the strong nuclear force and this helps to stabilise the nucleus – at least within limits.

48 As we said, the matter particles, hadrons are made up of quarks. Quarks exist in six different kinds – top and bottom, charm and

49 strange and up and down. These are all different, but only up and

down quarks are stable. Top quarks are actually the heaviest known particle with a mass more than 200 times that of a proton. Up quarks have an electric charge of plus 2/3rds of that of an electron and down quarks have a charge of minus 1/3rd of that of an electron. A proton is made up of two up quarks and a down quark and so has a net electric charge equal and opposite to that of an electron. A neutron is made up of two down quarks and an up quark and so has no electric charge. Quarks also have a property called colour charge, but I'm not going to go into that today – it's too complicated and not key to our understanding.

Protons and neutrons are quite heavy particles – a proton has a mass 1,836 times as much as an electron and a neutron is only slightly heavier than a proton – but most of their mass comes from the movement of the quarks and the energy involved in the gluons that hold them together rather than the substance of the quarks themselves. Most of you will know of Einstein's most famous equation $E = mc^2$. Well that shows that energy and mass are not only related but are aspects of the same thing. Most of the mass of any object in our world from your pet dog up to you owes most of its mass to the energy involved in holding it together. So the Higgs particle isn't responsible for all mass, only some of it.

50This interplay between mass and energy is seen wonderfully in giant particle accelerators like the LHC. Slam two particles together at very high speeds and the debris from the collision are likely to contain heavier particles than you started with because some of the energy of the collision is turned into mass. That's why you need such a large and powerful accelerator to make a very heavy particle like the Higgs boson. Particle physicists hunted for the Higgs for years. One of the problems is that it only exists for 100 trillionths of a trillionth of a second even if you can create it. In early 2012 the LHC was running at a rate of 75 million particle collisions per second, but the production of the Higgs is so unlikely that at this rate we would only expect to create one every 90 seconds or so. The other problem is that it needs so much energy to make it. No collider before the LHC really had much chance, but as of July 2012 we're pretty certain that the Higgs was detected at the LHC. The probability that what the LHC detected is NOT the Higgs is less than 0.0000003

The other kind of matter particles are leptons. Leptons are much smaller and lighter than hadrons. There are six kinds of leptons of which the most common are the electron and the neutrino. It needs 1,836 electrons to have the same mass as a proton and the neutrino has such a small mass that it hasn't been measured accurately yet, although it probably does have a very small mass.

HOW DOES THE STANDARD MODEL EXPLAIN WHERE MATTER COMES FROM?

We exist because of a huge number of fortunate 'accidents' or 'co-incidences' – taken together they're so unlikely that I prefer to call them 'God-incidences' or evidence for a creator designer.

51The fact that the sun burns at just the right rate, the fact that protons are stable, the fact that neutrons are slightly (but only slightly) heavier than protons, that the W boson is heavy and a number of other factors are all key to the universe being such as to permit our existence.

How old do you think you are? Well actually the atoms that you're made up of are at least 5 billion years old. Apart from hydrogen, the atoms which make up you and me were all cooked up inside a long dead star at least five billion years ago. The hydrogen was made shortly after the universe was formed around 13.8 billion years ago. So in a way you're between 5 and 14 billion years old.

You'll remember that the nucleus of a hydrogen atom is a proton and these protons form most of the mass of the sun (and indeed other stars) and fuel it today. At earthly temperatures complete atoms can survive, but above a few thousand degrees the electrons break free from the nucleus. That's what its like inside the sun – protons and electrons roaming around free.

Well these protons roaming around can bump into each other and initiate a process that converts four of them into the nucleus of helium (the next heaviest element after hydrogen). The mass of the helium nucleus plus the particles emitted is less than the mass of the four protons – so energy is released in the process. Remember Einstein's famous equation $E = mc^2$. Some of that energy eventually warms us here on earth.

52 The protons have to touch in order to fuse and build up helium. That's hard as their positive electrical charge makes them repel each other. But, a temperature of ten million degrees (which exists inside the sun) gives them enough kinetic energy to get close enough together to fuse. But, it's only just enough. The sun is some five billion years old and even now any individual proton inside it has only a fifty/fifty chance of having taken part in the fusion process. To put that another way, after five billion years, the sun has used up about half its fuel. Had the sun burned its fuel faster, it wouldn't have lasted long enough for us to exist.

The eventual result of all this is that four protons become a helium nucleus consisting of two protons and two neutrons plus two positrons and two neutrinos. So protons, or hydrogen nuclei, are the sun's fuel and helium is the ash left over.

The rate of this burning depends on the strength of the weak nuclear force which changes the proton into a neutron. Fortunately for us that force is weak and that weakness arises from the large mass of the W boson (which you will remember is one of the particles involved in transmitting the weak nuclear force). If the W boson was lighter the weak nuclear force would be stronger and the sun would have burnt its fuel too fast.

When 4,000 kg of hydrogen are converted into helium they make 3,972 kg of helium. The remaining 28 kg of mass is converted into energy in accordance with Einstein's famous equation $E = mc^2$ that we mentioned a minute ago. That's what happens in all nuclear processes, whether they be atomic bombs, H bombs or stars. Some of the mass is converted into energy. Because c , the velocity of light, is (as we've already seen) such a big number, you get a lot of energy.

Now if that conversion ratio of 0.007 was only very slightly less, say 0.006 (so that 24 kg of helium rather than 28 were converted to energy), then the reaction couldn't work in the sun or in any star and the universe would have no heavy elements and stars wouldn't shine. If the conversion ratio was slightly increased to 0.008 (so that 32 kg of helium rather than 28 were converted into energy) then conversion would be so prolific that all the hydrogen in stars would long ago have been burnt up and we wouldn't be here. This factor is critical to

at least one part in a million. Again good evidence for need for a creator designer.

Further if neutrons were lighter than protons then they would have emerged as the stable pieces in the origin of the universe and the universe as we know it wouldn't exist. Also the huge difference in mass between protons and electrons – you may remember the proton is 1,836 more times massive than an electron – is absolutely key to our universe being as it is.

In around five billion years time nearly all of the sun's hydrogen will be gone – turned into helium. But helium can fuse with further protons to build heavier elements, always releasing energy in the process. This can carry on all the way up to iron – which is the heaviest element you can build by fusion with release of energy in the process. Some stars collapse catastrophically and build elements even heavier than iron (absorbing energy in the process) – but that won't happen to the sun, it's too small.

So that's where you came from. The atoms which make you up were cooked in a star.

THE STANDARD MODEL AND THE HIGGS BOSON

The Standard Model of particle physics relies heavily on a branch of mathematics called gauge theory – which basically says that you can often describe things in terms of the symmetries between them and if they have symmetry they are often the same. A symmetry is an operation that doesn't change how something behaves in relation to **53**the outside world. So this ball has symmetry for the operation of rotation – it's always the same no matter how we rotate it.

All of the forces carried by bosons except for gravity and the Higg's field are unified by the gauge theory – so they all ought to be symmetrical. You'll remember we already mentioned that W^+ , W^- and Z bosons should have zero mass because they should be symmetrical with the other gauge bosons – photons and gluons. Clearly they aren't. Apart from the mass issue, the electromagnetic force carried by photons has infinite range, we see light from galaxies billions of light years away. Whilst the weak nuclear force carried by

W and Z bosons and the strong nuclear force carried by gluons are very short range.

The reason why the expected symmetries don't exist in our world is something called spontaneous symmetry breaking. That sounds complicated, but it's really quite simple [example with pencil]. As with the pencil, the symmetry is bound to break, but we can't predict exactly how until it happens.

54 So, with people, they are roughly equal or symmetrical at birth, but as time goes by the initial symmetry becomes less and less. By the time we turn twenty we have very different opportunities. A few can become concert pianists, a few Olympic athletes, many are working in factories. Looking at a nursery full of infants it would be difficult to predict how they would turn out, how the symmetry would be broken. That's what we mean by spontaneous symmetry breaking.

55 More at the level of physics, superconductivity is an example of spontaneous symmetry breaking, when the superconductor is cooled below a critical temperature – typically 160 degrees centigrade and all electrical resistance suddenly disappears. It's not a gradual change, it happens very suddenly as symmetry breaks. Superconductivity also shows how symmetry breaking can affect mass, when a mass-less photon enters a superconductor it suddenly acquires mass. Again at the level of physics, the earth shows how a symmetrical natural law – **56** the force of gravity – hasn't resulted in a completely symmetrical earth. It's flattened at the poles because it spins and there are mountain ranges because of volcanoes and tectonic plates.

Returning to the forces, they all had infinite range in the first few micro-seconds of the existence of the universe when it was very hot and energy levels were very high, but then the symmetry broke, because the Higgs field kicked in as the universe cooled, and the forces became as they are now. The Higgs field was what caused the symmetry to break. Also in the first micro-seconds of the birth of the universe all the particles had no mass, but then as things cooled and the Higgs field crystallised, symmetry was broken, and some particles acquired mass. The exact reason why they acquired mass is too complicated for us to consider today, but in essence what happened is that the particles interacted with the Higgs field and this acted as a

kind of brake on them. That brake is what we experience as mass. Some particles, like the photon, don't interact with the Higgs field at all and remain without any mass. In a way the Higgs field does away with the idea of mass – mass is simply the interaction between a particle and the Higgs field.

57At first, 13.8 or so billion years ago, the universe was too hot for the laws of nature as we now experience them to materialise, but in the blink of an eye the universe grew to the size of a beach ball and cooled to 10 thousand trillion degrees Celsius. Just cool enough for the Higgs field to come to life. In that instant some particles acquired mass, made slow and heavy, like flies caught in a dish of soup. Without the Higgs field the universe as we know it could not exist. Matter simply wouldn't clump together. Of course, the Higgs boson, which gives expression to the Higgs field was key to all this. Theoretically we could change things again by heating space up to a million billion degrees, so that the Higgs field was retriggered, but fortunately we can't do it. If we could matter might collapse and all the forces as we know them might change.

The idea of combining spontaneous symmetry breaking with gauge theories was what Francois Englert and Robert Brout first came up with in Brussels in 1962 and independently a few months later Peter Higgs came up with the same idea. There is a particle whose existence is a consequence of spontaneous symmetry breaking – the Higg's boson. As I already said the Higg's boson should really be called the EBH boson, but somehow Higgs got the lions share of the credit.

The existence of the Higg's boson is foundational to the Standard Model of particle physics. If it didn't exist then the Standard Model would be completely wrong.

The use of the idea of spontaneous symmetry breaking in the Standard Model has profound consequences not just for the laws of nature but for the larger question of what a law of nature is. Before the Standard Model scientists used to think that the properties of all the particles (including the force particles, the bosons) were determined by eternal laws of nature. But, in a theory with spontaneous symmetry breaking the properties of the particles depend on how the symmetry broke.

The symmetry could break in different ways depending on temperature, density and so on in the early universe. The particles depend not just on the equations of the theory but on which solution to the equations happens to apply in our universe. It's like when you throw a ball in the air. Newton's Laws, the equations of motion, govern its path. But, the exact trajectory of the ball depends on the initial conditions – how hard and what angle you throw the ball. So the path of the ball depends on what solution to Newton's Laws applies. It's the same with spontaneous symmetry breaking.

Even worse than that the properties of particles could be different in different areas of the universe they could even change with time. All the evidence we have suggests that they don't vary in these ways – that in itself is evidence for a creator designer God who sustains his universe. But there's much stronger evidence than that for a creator designer as we shall see later.

In spontaneous symmetry breaking there is a physical quantity which signals that the symmetry is broken and how it is broken. This is the Higg's field and the force associated with the Higg's field is carried by the Higg's boson. Unfortunately for scientists theory didn't exactly predict the mass of the Higg's boson – before the experiments at the LHC all we knew was that it must be more than 120 times the mass of a proton and if the LHC results really are the Higgs we now know its mass is about 133 times that of a proton. It's this large mass that has made the Higgs so difficult to detect, because only very high energy accelerators can hope to produce it – you'll remember we talked a little bit about mass-energy equivalence earlier.

So the gauge principle combined with spontaneous symmetry breaking unifies three of the four forces – the electromagnetic force, the weak nuclear force and the strong nuclear force. They're all tied together in the Standard Model. Of course, it doesn't explain why there are force particles and matter particles. An extension of the Standard Model called “Super-symmetry” or SUSY for short does – but there's absolutely no evidence for it (and quite a lot against it, including the latest results from the LHC which have failed to find any of the particles it predicts) so I'm not going to talk about it today.

Maybe the new runs of the upgraded LHC this year will turn up some evidence for SUSY this year - but I'm predicting they won't.

The Standard Model also fails to explain what sets the constants in the Standard Model and what makes the ratios between them so big. It's really surprising, for example, that the weak nuclear force is 10^{32} times the force of gravity. Even worse, how do these constants stay where they are? The stability is puzzling because quantum physics has a strange tendency to pull all the masses together toward the value of the Planck mass – that's about 2×10^{-8} kg, colossal for a particle – about ten, billion, billion protons. I'm not going to explain exactly why, this pull arises, it's just too complex, but it's rather as if the levers we use to tune the constants were connected with rubber bands which are steadily tightening. This doesn't happen to most of the force particles, the bosons, or to any of the matter particles, the fermions – their masses are what we call protected. It's just a problem for the Higgs, which should have a mass 100 million billion times larger than it does.

To keep the large ratios that we actually have in the Standard Model, we have to pick the values of lots of constants that are able to be specified individually and independently with exquisite precision. Otherwise the mass of the Higg's would be pulled up to the Planck mass and the universe would be very different. It turns out that we have to tune 25 of the independent constants of the Standard Model (fifteen relating to the masses of the quarks and leptons, eight relating to quark and neutrino interchanges and two basic physical constants – the fine structure constant and the strong coupling constant), each to an accuracy of 32 decimal places to keep the mass of the Higg's down where it is and make the Standard Model work. The odds of that happening by chance are less than 1 in 10^{30} .

Are you beginning to see why I said the Higgs boson was appropriately named the God Particle. What could have tuned all these independent values of the Standard Model so accurately apart from a creator designer God. When the USA was considering building a huge particle collider called the Superconducting Super Collider a congressman asked one of the scientists advising on the project "Will this make us find God?". Well, of course we can't find

God in a machine we construct, God doesn't live in temples built by human hands, but I hope you can see how it can help us see the magnificent complexity of God's creation and why we need to assume a creator designer to explain the world in which we live. And you know this isn't just my opinion, many scientists are of the same view. Let me just read to you a few sentences from the last chapter of a book on quantum gravity by Lee Smolin. Lee Smolin is one of the top ten theoretical physicists in the world and he's certainly no Christian – he'd like to be in the Richard Dawkins camp, but he's too intellectually honest. [reading]

CONCLUSION

Now, why should we assume that the laws of physics which apply here, will apply on the moon or in the next galaxy. It's really a restatement of the argument originally raised by philosopher Descartes. Peter Higgs himself raised this question before the Maxwell Society at King's College London in 1950. The notes of the meeting say that Higgs' point "aroused considerable controversy". Actually, there is no reason to assume a continuity and conformity of physical laws, apart from faith in a God who made and sustains the universe according to his unchanging principles

Oh, physicists have tried various ways to avoid this problem, but so far nothing has worked. As we've already said there is no evidence for Supersymmetry (which anyway only deals with some aspects of the problem), string theory is a failure and we haven't even been able to reconcile quantum theory with theories of gravity. Indeed many scientists almost hoped that we wouldn't in fact discover the kind of Higgs boson that would be consistent with the Standard Model, because as we've already seen the Standard Model requires so many independent constants to be so precisely adjusted that it speaks loudly of a creator designer. Well, it appears the kind of Higgs we have is exactly the kind the Standard Model would predict.

There are lots of other problems too. When matter originated within the early universe both particles and anti-particles were created in almost equal numbers. In fact we would have expected them to be created in *exactly* equal numbers. Fortunately, that wasn't the case, otherwise the universe might contain less matter than is necessary for

life to exist and/or matter and anti-matter would always be engaging in spectacular mutual annihilation with very bad results for us if happened anywhere nearby. For some reason there was a slight imbalance between matter and anti-matter in the creation process, of just the right amount to leave behind the amount of ordinary matter needed as all anti-matter was annihilated in collisions with ordinary matter. But, this is entirely contrary to theory, and remains a mystery only explicable on the basis of the intervention of a creator designer.

Finally there is the problem of dark matter and dark energy. Recent measurements of the motions of stars in the outer reaches of galaxies, galaxies in clusters of galaxies and the expansion of the universe reveal that either our theories are completely wrong, or the universe consists mostly of the unknown. If the universe does consist mainly of the unknown then some 68% of it must be dark energy, driving the accelerating expansion of the universe, 27% must be dark matter, needed to explain motion in clusters of galaxies and of stars in the outer reaches of each galaxy and only 5% in the form of the normal matter we've been looking at today. At one time some scientists thought that the dark matter might be mostly some sort of Supersymmetric particle – a WIMP or weakly interacting massive particle. But, as I've already said the Higgs fitting neatly into the Standard Model makes Supersymmetry less likely and there isn't even one piece of evidence for Supersymmetry and lots against it. Also the Standard Cosmological model fits quite well with the Standard Model of particle physics in predicting the kinds and amounts of matter that exist (apart from the matter – anti-matter issue we've discussed) and the latest mapping of the cosmic microwave background radiation from the Planck satellite tends to confirm the standard cosmological model. It would be hard to accommodate the production of huge quantities of exotic particles in either of these standard models. Perhaps the laws of motion, the law of gravity, needs to be modified when the forces are very weak and/or when very large distances are involved, but we just don't know. There is a theory of that kind called MOND or modified Newtonian dynamics, which better explains the dynamics of galaxies and why the dwarf galaxies around the Milky Way (like the greater magellanic cloud) have stable orbits. MOND doesn't completely explain the dynamics of clusters of

galaxies, but could probably be enough of the explanation to do away with the need for dark matter comprising unknown particles. Unsurprisingly, not a great deal of work has been done in this area because again it's pointing in the direction of need for a creator designer.

What I can say in conclusion is to return to the initial statement that the Higgs Boson is both appropriately and inappropriately named as "The God Particle". It's appropriately named because it gives the whole universe mass, it makes it possible for us to be here to discuss it and most importantly because, being the way it is, it points strongly to the need for a creator designer God. It's also inappropriately named, because as we've seen there's simply so much, so many issues that we don't yet even have a clue about. We need to abandon our pride and arrogance and admire the wondrous complexity of creation – and I do mean creation. There's no way this universe arose by accident.