The Higgs Boson

C.Jeynes, Guildford 30th August 2012

There is today great excitement about the "observation" of the long-sought *Higgs Boson* reported (unofficially) on 4th July 2012. In this essay I will try to describe first what a Higgs Boson is, with an Introduction to the events, then a very simple description of the appropriate physics that should be accessible to everybody ("Glossary"); then I will show why I think that Christians should be interested in it. I list references at the end.

Introduction to the events

> A Higgs boson is a massive scalar excitation remaining after the excitations of the argument of the condensate wave function of the symmetry-breaking scalar multiplet have combined with some of the gauge fields to provide the longitudinal components of massive vector bosons.
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> Peter Higgs, *Comptes Rendus Physique*, 2007 (*op.cit.*)

The "Higgs boson" was predicted by Peter Higgs in 1964, but his was only one (important) contribution to the vigorous theoretical developments at the time. François Englert and Robert Brout actually had precedence over Higgs since they discussed the 'Higgs mechanism' in much greater generality than Higgs had done; their paper appeared in the same issue of *Physics Review Letters* but was received earlier and was based on earlier work, namely the tree approximation to the vector field propagator in spontaneously broken gauge theories by Feynman diagram methods, whereas Higgs started from classical Lagrangian field theory. The same year Gerald Guralnik, Carl Hagen, and Tom Kibble also showed how a massive boson could be consistently expected from the field equations, in a paper which cited the other two. All three of these papers are listed for 1964 on the *PRL Milestone Papers* website (http://prl.aps.org/50years/milestones#1964), and all six authors are considered joint "inventors" of the Higgs boson, for which it is confidently expected that a Nobel Prize will be awarded (Brout died in 2011).

The Higgs boson is the final elementary particle predicted and required by the Standard Model of elementary particle physics which had not, prior to July 2012, been observed via particle physics experiments. It is the quantum excitation of the Higgs field, and the non-zero value of the ground state of this field gives mass to the other elementary particles such as quarks and electrons through the Higgs mechanism.

The Standard Model does not predict the mass of the Higgs, but an excitation with properties consistent with the Higgs at about 125 GeV (133 proton masses) was independently reported in July 2012 by both the ATLAS and the CMS detector groups of the Large Hadron Collider with experimental uncertainties approaching 5sigma (that is, a probability of less than one in a million of the observation being a chance event). Both of the ATLAS and CMS detectors are complex and gigantic (that is, they are comparable to the size of cathedrals). "ATLAS" stands for "A Toroidal LHC Apparatus" and specifically recalls the Greek Titan who held up the celestial sphere: this is since the detector was designed to look for the Higgs, a particle fundamental to the structure of the universe. "CMS" means "compact muon detector", where "compact" does *not* mean "small"!

To detect the Higgs boson needs energies greater than 1.4 TeV; the LHC is currently at 8 TeV, accelerating two beams of 4 TeV protons in clockwise and counter-clockwise directions before finally smashing them together (hence "*Collider*") in the detectors. It is designed for 14 TeV (2 times 7 TeV).

Physics glossary

1 eV [one "*electron volt*"] is an energy of 16.10^{-20} Joules, so a GeV ["*giga*-eV"] is a thousand million eV, and a TeV ["*tera*-eV"] is a million million eV or 0.16 microJ. It is interesting that there are cosmic rays with energy many millions of times greater than this, and we *still* don't know where they come from nor how they arise!

Bosons are elementary particles (or collections of elementary particles) capable of occupying the same quantum state, unlike *fermions* which obey Wolfgang Pauli's *exclusion principle* (Pauli, 1925). Fermions are named after Enrico Fermi because they obey *Fermi-Dirac statistics*, proposed by Fermi and Paul Dirac independently, although Fermi had the precedence (Fermi, 1926; Dirac, 1926). So electrons are fermions and photons are bosons. Atoms exist because the electrons have to space themselves out (because of the exclusion principle) in the electron *shells* of the atoms, and that is where chemistry comes from. *Bose-Einstein statistics* was first proposed by Satyendra Bose in a letter to Albert Einstein (which he translated into German) in 1925. A real case of "*Bose-Einstein condensation*" was first recognised by Fritz London in 1938 for liquid helium. "Boson" and "fermion" are terms apparently invented by Dirac in 1945; Dirac is the brilliant British physicist responsible for predicting the existence of antimatter (*positrons*) in 1931, which is exploited in the PET ("positron annihilation tomography") scanners in constant use in many hospitals today.

The Fermi-Dirac and Bose-Einstein *statistics* are important in *quantum mechanics* specifically because it is *impossible in principle* to say precisely *both* where a very small particle is *and* how fast it is going: one can only speak about its joint position and momentum in probabilistic (statistical) terms. This is an imprecise statement of *Heisenberg's Uncertainty Principle* (Werner Heisenberg, 1927).

Quantum mechanics is the physics of the very small. Everyone knows that everything is made of atoms – matter comes in little chunks which cannot be divided indefinitely. It turns out *both* that energy also comes in little chunks ("*quanta*": see Max Planck, 1901) *and* that mass and energy are equivalent through $E=mc^2$ (Einstein, 1905).

Bose-Einstein condensation is the effect one gets when a collection of particles (not usually bosons themselves) can form a boson under certain circumstances: *liquid helium* (the ^{3}He isotope) was the first example, discussed by London in 1938. Liquid ^{3}He is a *superfluid* specifically because it forms a B-E condensate.

Another example is *superconductivity* (see the important "BCS" paper, 1957), which occurs because pairs of electrons (the original *fermion*) can form a *Cooper pair* (Leon Cooper, 1956), which is a *boson*. Superconductors are central to achieving the very high magnetic fields essential to the operation of the LHC itself, and for many other purposes (including the magnets in the MRI ("magnetic resonance imaging") machines that are in many of our hospitals).

The *Standard Model* of elementary particles is a heavily mathematical theory which aims to integrate all the knowledge we have of the behaviour of quantum particles. It specifies field equations for nuclear phenomena comparable to those we are familiar with in electromagnetism (the *Maxwell equations*, James Clerk Maxwell 1861). Maxwell pointed out later how particles ("photons") could arise from these field equations, and Einstein got the Nobel Prize by putting this idea together with Planck's to explain the photoelectric effect (Einstein, 1905b); in the same way all the field equations of the Standard Model also have particles associated with them.

So far we have mentioned quite simple stuff. However, *gauge theories* are a further level of sophistication. A definition of "gauge theory" (from Wikipedia) is, "*a type of field theory in which the* Lagrangian *is invariant under a continuous group of local transformations*". The best introduction to the *Langrangian* in mathematical physics I know of is in Roger Penrose's magisterial "*The Road to Reality*" (2004).

Joseph Lagrange was an Italian nobleman who succeeded Leonhard Euler as Director of Mathematics of the Prussian Academy in 1766. Euler discovered what Richard Feynman has called "the most beautiful formula in mathematics": the identity $e^{i\pi} + 1 = 0$ which uses five of the fundamental numbers in mathematics, namely e, i, π, 1, 0. Lagrange moved to France in 1787 and remained there until his death in 1813. His masterpiece on mechanics was published in 1788; printed under the supervision of Adrien-Marie Legendre, another legendary mathematician, inventor of the eponymous Legendre polynomials.

Wikipedia states (correctly) that :- "Lagrangian mechanics is a re-formulation of classical mechanics using *Hamilton's Principle* of stationary action." William Hamilton was an outstanding Irish mathematician who reformulated Lagrangian mechanics into a particularly beautiful and symmetrical system (Hamilton, 1834) that amazingly remained valid even when the quantum mechanics overthrew Newtonian mechanics in the early 20th century.

The point about the Lagrangian is that it describes any system in a (multi-dimensional) *configuration space* in which the state of the system at any time can be represented by a point, with the time evolution of the system described by the locus of the point in the space. The formalism allows the *principle of stationary action* to be expressed elegantly, and, more importantly, to be *used* effectively to solve a huge variety of problems. In particular, the Lagrangian can be used to demonstrate how specific systems are subject to various *conservation laws* (of energy, of momentum, of angular momentum etc). These conservation laws express the *invariance* properties of the system.

Now, the *gauge* in the gauge theories that have been mentioned can be understood as the set of rules for handling the *metric* (the unit of measurement) of the configuration spaces in which the system is being described, bearing in mind that we are speaking of a space usually of very large (possibly infinite) numbers of dimensions. This is quite a high level of abstraction!

When Higgs speaks about *massive scalar* and *vector* bosons in the opening definition, he is distinguishing between particles with and without *mass* (the photon has zero rest mass for example), and between particles with and without *spin* (the photon also has zero spin, making it a massless scalar boson). Other gauge bosons (with unity spin) include *gluons* (massless vector boson), *W and Z bosons* (massive vector bosons), and *vector mesons* (made of a quark and an anti-quark; these are also massive vector bosons).

Finally, Richard Feynman got the Nobel Prize in 1965 for his use of so-called *Feynman diagrams* (instead of the classical analytical treatment) to dramatically advance knowledge of *quantum electrodynamics*. His beautiful little book *QED* (1985) is an all-time classic exposition for everyone of what *photons* really are.

Why should Christians be interested in the Higgs?

Think what is going on. About 50 years ago a few physicists wrote down some equations that persuaded mankind to invest some six thousand million Euros and thousands of man-years of labour to build the Large Hadron Collider (on time and on budget – if you want things done properly, give them to physicists to do!). And it turns out the equations are correct! This strikes me as being an extraordinary state of affairs. Why should we conceive either that the world is like that, or even that we could ever know it at such detail?

You could never make this stuff up! Even only a hundred years ago, if someone had told this story people would have thought he was stark staring mad. But God's plan has always been hard to understand: sometimes I think he takes a special delight in baffling us! *Foolishness to the Greeks* … (1Cor.1:23); *past knowing* … (Rom.11:33); *No eye hath seen, nor ear heard* … (1Cor.2:9; Is.64:4); *my thoughts are not your thoughts* … (Is.55:8f); *they didn't understand what he was saying* … (Luke 2:50; John 16:18). These Scriptures refer to God's plan for our salvation of course, but God's ways are coherent and his design of his Creation, which he said repeatedly was *good*, *good* and *very good* (Gen.1:4, 10, 12, 18, 21, 25, 31), is all of a piece with his design for his children.

Whereas the bankers indulge their gambling egged on by the people, who desire to indulge their greed, it is the physicists who live in the *real world*, confronted as they are every day by the astonishing intricacies of the handiwork of God – rightly did David sing, *the heavens declare the glory of God* (Ps.19:1)!

Of course, the Higgs Boson wasn't Higgs' original idea, just as bosons themselves were not Bose's original idea – God thought of them first, and didn't only think them but *spoke them into being*: they are his creatures. But the physicists are right to give the creatures their names after their discoverers, because it is good to remember the *stories* that accompany the discoveries. Just because physics is not about flesh and blood but rather about the internal structure and consistency of God's creation doesn't mean that there is no *story*, no excitement! On the contrary, God delights in story, and he builds it into everything he does. In this we only reflect God's character, as expected since we are his children, made in his *image* (Gen.1:26f; 9:6; Rom.8:29; 1Cor.11:7; 2Cor.4:4; Col.1:15).

Everybody, and physicists in particular, believe that Nature abides by natural Laws. Why does the sun rise in the morning? Because it is law-abiding! And of course physics is the sustained effort of discovering these laws of nature. Isaac Newton's insight, that the existence of the inverse-square law of gravitational attraction was sufficient to explain the orbits of the planets, largely accounts for the sun rising regularly every morning. But why does the inverse-square law exist, and why does it operate? These are philosophical questions not accessible to physics. The details and scope of the natural laws can be elaborated and extended, but the questions surrounding their very existence are of a different order.

The question can be posed a different way. Who made the laws? Michael Frayn in his elegant and deeply thoughtful book *The Human Touch* (2006) identifies Descartes as first speaking explicitly of natural *law* (in his *Discourse on Method*). Of course, for Descartes this was a natural way for a Christian to speak, and he assumed that everyone knew that God had made the laws. Today most people treat this as a metaphor since they deny the existence of God, but philosophically the question remains. Without God (or some Lawgiver) we have no philosophical reason for believing that the sun will rise in the morning. David Hume pointed out long ago (in *An Enquiry Concerning Human Understanding*) that induction ("it always has so it always will"!) won't suffice, even though we would be crazy *not* to believe it. Actually, our sanity *depends* on our (tacit) recognition that natural laws exist.

It is specifically the monotheist religions (the Jews, Christians and Muslims) that, recognising a Creator, have an adequate philosophical *reason* for the existence of natural law. In particular, it was the Christians who developed this understanding during the High Middle Ages specifically into the scientific enterprise we know today. The story is told in detail by Stanley Jaki in his book *Science and Creation* (which I have abridged). I regard the first Creation account (Gen.1) to explicitly state this since it very deliberately presents the celestial bodies both as God's *timekeepers* and as his *rulers*:

> And God said, Let there be lights in the firmament of the heaven to divide the day from the night; and let them be for signs, and for seasons, and for days, and years: and let them be for lights in the firmament of the heaven to give light upon the earth: and it was so. And God made two great lights; the greater light to rule the day, and the lesser light to rule the night: he made the stars also. And God set them in the firmament of the heaven to give light upon the earth, and to rule over the day and over the night, and to divide the light from the darkness: and God saw that it was good.
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> *Genesis* 1:14-18

The "lights" are for "signs and seasons and days and years": they "rule" the day and the night! All civilisations have recognised the regularity of the heavens, very often with astonishing sophistication. The very development of mathematics was underpinned by the regularity of the heavens. Note that the *text* of Genesis that we have long predates Hellenic mathematics, probably being more or less contemporary with Homer, and the oral tradition underlying the text may be *millennia* older still. Here is the philosophical underpinning of the *idea* of natural law: the sun and the moon *rule* the day and the night, and they in turn, as creatures of the Creator, are ruled by God.

When David sang "*The heavens declare the glory of God*" (Ps.19) I have no doubt that he specifically had this Creation story in mind. And the purpose of the Psalm was to continue from consideration of the Creation to meditation on the character of the Creator: God's physical reliability (in the matter of the sun rising every morning) is an earnest of his underlying reliability in more weighty matters :-

> The law of the Lord is perfect, restoring to life
> The testimony of the Lord is sure, making wise the simple.
> The statutes of the Lord are upright, delighting the heart
> The commandment of the Lord is pure, enlightening the eyes
>
> King David, *Psalm 19*:7f

Christians watch advances in physics with pleasure that God delights in making himself known to mankind, both in these simple matters of the structure of the created world as also in the more complex matters of our motivations and purposes, of the desires of our hearts and our burdens of guilt, and of our very grasp on sanity itself. They reflect with pleasure on God's unaccountable determination to be compassionate and sympathetic towards us, and (being thorough and consistent) even supporting us ontologically and epistemelogically :-

> The eternal God is thy refuge
> and underneath are the everlasting arms
>
> The Blessing of Moses, *Deuteronomy* 33:27
> (see also *Psalms* 17:8; 36:7; 91:1; *Song of Solomon* 2:3; *Hosea* 14:7; *Mark* 4:32)

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