The Large Hadron Collider: Who gives a Higgs Boson Anyway?

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The Large Hadron Collider

By now the Large Hadron Collider or LHC and the Higgs boson have become big news. Countless newspaper articles over the past year or so have tried to keep their readers up to date on the progress towards finding the so-called 'God particle'. Despite the acres of newsprint[1] and millions of web pages [2] how many of us actually have a real grasp of what is going on in the tunnels below the Swiss-French border close to Geneva? Perhaps that is not surprising as the newspaper articles and webpages have attempted to explain the significance of the most advanced physics experiments that are being done with the most elaborate and complex machine ever built by humankind in a few short paragraphs. A couple of columns inches squeezed between the quarter page advertisements in a weekend supplement isn't perhaps sufficient to give the non-physicist enough information to get more than a superficial grasp of what is being attempted and achieved scientifically or, more importantly, form an opinion as to the usefulness and worth of the biggest scientific experiment ever. Nevertheless the LHC and the Higgs Boson have become part of our culture and might also be described as household terms. Authors of popular fiction like Dan Browne have embraced the perceived weirdness of the physics being done at the LHC to create science fiction. In the novel *Angel's & Demons* antimatter supposedly created in the LHC is used as a weapon against the Vatican[3]. The Irish crime novelist, John Connolly, has published two children's novels[4][5] in which the hero, a boy called Samuel Johnson and his dachshund, fight the forces of evil when the (not very bright) scientists running the LHC manage to unwittingly open the gates of Hell and release a horde of devils and demons to roam the Earth and create mayhem and havoc.

On top of this, a YouTube video that shows a simulation of the earth being 'swallowed' into a black hole that some alarmists had predicted would be created when the LHC is running has had over nearly 5 million hits since it was posted in February 2008 [6]. The video is a graphic illustration of the claim (made before the LHC went operational) that it would destroy the Earth and all humanity. The claims were widely reported in the period 2008-2010 and even led to legal challenges in USA and Europe attempting to prevent

[1](1) For example 'Scientific breakthrough - Discovery thought to be the elusive 'God particle'' *Irish Times* , 5 July 2012

[2](2) A *Google* search on 'Large Hadron Collider' returned 4.96 million results on 7 January 2013

[3]*Angels & Demons*, Dan Browne, Pocket Books, USA 2000

[4]*The Gates*, John Connolly, Hodder & Stoughton, GB and Ireland, October 2009

[5]*Hells Bells*, John Connolly, Hodder & Stoughton, GB and Ireland, May 2011

[6]`http://www.youtube.com/watch?v=BXzugu39pKM` accessed 7 January 2013

the operation of the LHC. [7]

Meanwhile, less fanciful criticism has raised more serious questions about the benefit of the science being done at the LHC. The experiments carried out there have been criticised by some scientists who have argued that the huge sums of money that the LHC has cost could have been better spent on other projects. For example David King, former chief scientist in Britain, argued in 2008 that Britain should cease its contribution to CERN, the European Centre for Nuclear Research, the international organisation that operates the LHC and divert the resources to combating climate change instead.[8]

In this article we will therefore attempt to explain in terms that everyone can understand both the technology involved at the LHC and the scientific significance of some of the experiments carried out there. The prime motive is to put before the reader some of the detail of how and why research like that done at the LHC has come about in order that they may make a more informed opinion as to its worth. We will also briefly discuss the costs and one or two arguments relating to the benefits of such research. It seems to the author that this is the bare minimum of information required for any democratic debate on such a subject.

What is the Large Hadron Collider?

First and foremost it needs to be understood that the LHC is the largest and most complex machine ever built by humans. At its heart is a pair of vacuum tubes or pipes that are located in a ring-shaped tunnel that measure 27 km (more than 17 miles) in circumference. Subatomic particles are accelerated to almost the speed of light and travel around the rings guided by 1,600 huge superconducting electromagnets each weighing 27 tonnes. These magnets are cooled with liquid helium to a temperature of -271.3^0C - colder than outer space - almost at absolute zero, the lowest theoretically possible temperature. The tunnel runs between 50 and 175 metres below ground level and crosses the border between Switzerland and France near Geneva where CERN is located.[9]

The particles that are accelerated in the ring-shaped vacuum tubes reach speeds approaching the speed of light (99.99999%c - where c is the speed of light) and travel in one direction in one ring and in the other direction in the other one. The two rings cross at four places and so the particles going in opposite directions are made to collide at these four points where the rings intersect. These intersections are located in four huge underground caverns that house the detectors that are trying to record the outcomes of collisions of the particles.[10]

What is a particle accelerator?

The LHC is the latest and most power in a series of so-called particle accelerators that have been the workhorses of nuclear physics since the 1930s. In order to in-

[7] A summary of the safety concern claims and their rebuttals can be found at `http://en.wikipedia.org/wiki/Safety_of_particle_collisions_at_the_Large_Hadron_Collider` accessed on 8 January 2013.

[8] Martin O'Neill, 'Politics of proton smashing', *New Statesman*, 17 September 2008, `http://www.newstatesman.com/international-politics/2008/09/physics-lhc-cern-scientificaccessed6May2013`

[9] `http://lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/accessedon8January2013`

[10] see footnote 9

vestigate the structure of the atom and probe the newly discovered atomic nucleus, scientists first accelerated charged particles at solid targets. In 1932, a British and an Irish scientist (John Cockroft and Ernest Walton) accelerated protons at a solid lithium target and observed that the protons caused the lithium nucleus to disintegrate and together with the proton form two helium nuclei.[11] They used high voltages to accelerate the protons and give them the necessary energy to break into the lithium nucleus and ultimately cause it to disintegrate. This experiment was hailed at the time by popular culture as the first 'splitting of the atom'. [12] Perhaps more importantly Albert Einstein regarded the Cockroft and Walton experiment as the first experimental demonstration of his famous equation $E = mc^2$. [13]

The apparatus they designed was the first particle accelerator and was of a type now known as a 'linear accelerator' because the particles are made to travel in a straight line by the application of a very high electrical voltage - up to 700,000 V in their case. It was largely built by the Irishman, Walton [14] and the technology they developed, the Cockroft-Walton voltage multiplier, continues to be used today, not only in particle colliders such as the LHC, but also in many every day electronic devices that use very high voltages, such as X-ray machines and photocopiers.[15]

Other physicists at the same time began to experiment with radio waves rather than high voltage as a means to accelerate charged particles and they also used magnets to bend the beams of particles so that they travelled in spirals [16]. In the 1940s others managed to construct a machine in which the particles were accelerated around a ring-shaped vacuum tube - a so-called 'synchrotron'.[17] The synchrotron has two advantages for nuclear research. Firstly, the energy of the particles could be increased at every revolution around the ring by pumping in more energy by means of radio waves and secondly, two 'beams' of particles could be made to circle in opposite directions in two rings that intersected at one or more points. The particles could then be made to collide with enormous energy. Accelerators designed to make the particles collide are often referred to as 'particle colliders'.

Depending on the particles and the energy of the collision, the colliding particles were either caused to split apart into smaller particles or to combine to form new larger ones. By detecting and observing these collisions and their by-products scientists working over the intervening decades since Cockroft and Walton have used particle accelerators to discover the physics of the sub-atomic world.

[11] http://www.nobelprize.org/nobel_prizes/physics/laureates/1951/walton-bio.html accessed on 8 January 2013

[12] *Ernest Thomas Sinton Walton (1903-1995): The Irish Scientist.* Vincent J. McBrierty, Trinity College Dublin Press, 2003.

[13] The YouTube video http://www.youtube.com/watch?v=CC7Sg41Bp-U (accessed on 8 January 2013) is an evocative recording of Einstein explaining the significance of his equation and saying the that it was 'demonstrated experimentally by Cockroft and Walton in 1932'.

[14] see footnote 11

[15] http://en.wikipedia.org/wiki/Cockcroft%E2%80%93Walton_generator accessed on 8 January 2013.

[16] http://en.wikipedia.org/wiki/Cyclotronaccessedon8January2013

[17] http://en.wikipedia.org/wiki/Synchrotron accessed on 8 January 2013

What makes the LHC so special?

The LHC is the latest and most advanced of these particle accelerators and is, in fact, connected to a series of accelerators beginning with a linear accelerator (like Cockcroft and Walton's) followed by a number of synchrotrons culminating with the largest ring of 27 km in circumference. What makes it so special is the huge energy that the particles attain in the final and largest of the rings. It currently accelerates protons to an energy of $3.5TeV$ ('tera electron-volt') which is equivalent to using a voltage of 3.5 thousand million volts. When two protons travelling in opposite directions in the two rings collide at one of the intersection points, the collision has an energy of $7TeV$ ($3.5TeV$ from each proton). This energy is far larger than any achieved in previous colliders built anywhere in the world.[18] Hoverer, it is not yet running at full energy and it is planned to double the energy and achieve the design specification energy of $14TeV$ in 2014.[19]

In any ring shaped accelerator the practical limit to the energy of the particles that can be attained is the magnetic field of the 'bending magnets'. If the energy becomes too great or the magnet field is not strong enough, the particles fly too fast as they approach the corners and crash into the wall of the vacuum tube - just like a car travelling too fast fails to take a corner at high speed. So the designers of the LHC faced a huge engineering challenge in accelerating the particles to the design energies and still managing to keep them in the ring. They faced a choice to either make the ring of a really enormous diameter and use the magnet technology that was available at the end of the 20th century or to try to fit the ring into a pre-existing 27 km circumference tunnel that had been built for a previous accelerator - the LEP collider. To do this they had to develop suitable superconducting electromagnet technology to produce the enormous magnetic fields required to bend particles in a tight enough curve to fit inside the existing ring. Given the probable difficulties in building a ring of diameter of 60 km or 90 km circumference in a populous part of central Europe, they chose to use the existing 27 km long tunnel and develop a new generation of superconducting magnets that could produce high enough magnetic fields.[20] For comparison, it is interesting to note that a similar American project to build a collider near Dallas Texas - the 'Superconducting Super Collider' (SSC) - would have had even three times the energy of the LHC and would have required a ring that was also approximately three times larger diameter (approximately 80 km in circumference). The SSC project was cancelled in 1993 by the US Congress.[21]

Beyond the elements - smaller than atoms

When we try to understand the research that is done at places like the LHC it is useful to first recall the state of our knowledge in the early part of the twentieth century when nuclear research began. The ideas about what makes up the universe were pretty much those which we all have since learnt in school. All matter seemed to be

[18] `http://en.wikipedia.org/wiki/List_of_accelerators_in_particle_physics` accessed on 9 January 2013

[19] see footnote 9

[20] see footnote 16

[21] LHC Design Report Volume II: accessed on [22] on 9 January 2009

made from the so-called 'elements'[23] - over a hundred or so substances; mostly solids, a few liquid and some gasses that combine to form all other substances. The elements can be arranged according to their properties and are represented in the periodic table. The smallest unit of an element, a tiny particle far too small even to be seen with the best microscopes, the atom, was of course well known and was the limit of our knowledge up to about a hundred years ago.

In 1932 with the discovery of the neutron[24] the internal structure of the atom itself was becoming clearer - at its centre is the positively charged nucleus which contained by far the lion's share of the mass of the atom squeezed into a very small space. Together with the much tinier (negatively charged) electrons that orbit around the nucleus at relatively large distances it emerged that every atom - and therefore it was assumed all matter in the universe - was made up of a combination of just three sub-atomic particles: protons, neutrons and electrons. In addition to matter it was known that light and energy also exist and the picture seemed to be complete.

The first question that the nuclear physicists turned their attention to was whether they could modify the nucleus in any way - in fact the first such successful experiment to do that had been carried out by Rutherford in Manchester in 1917 when he converted or 'transmuted' nitrogen into oxygen using alpha particles. However, a full explanation of the experiment was not then possible.

So what are the results of over 80 years of intensive scientific research using particle accelerators to collide protons and other particles together? It is no exaggeration to say that the physics that has been discovered is incredible and beyond the fantasies of a thousand Dan Browns.

Nuclear scientists have gone far beyond the goal of splitting a nucleus into its constituent parts or seeing if they can combine them into new arrangements to form new elements. All of this has of course been done and the world has learnt the consequences of splitting some nuclei and combining others and the release of energy that can go along with it in some cases. Nuclear weapons and nuclear power are not the subject of this article and deserve separate consideration.

Instead we will concentrate on the revolutionary ideas that have been discovered by studying the results of colliding particles like the proton in accelerators with very high energy.

Firstly, the most obvious question to address is: what makes up protons, neutrons and electrons? If the atom -once considered indivisible and the fundamental particle - is made up of the three subatomic particles, are they themselves made up of even smaller particles? And indeed it has

[23](19) The elements are chemically immutable but they combine in myriad of different ways to form all the matter that we can see, feel and touch around us. By combining atoms of different elements 'molecules' could be formed that formed the basic units of an almost infinite number of new substances with properties than can be wildly different from the elements from which they are made. It was also learnt that that billions upon billions of atoms or one or more elements of can arrange themselves in ordered 'crystals' that again had different properties - for example some conducted electricity (like copper or iron) and some were insulators (like iron oxide).

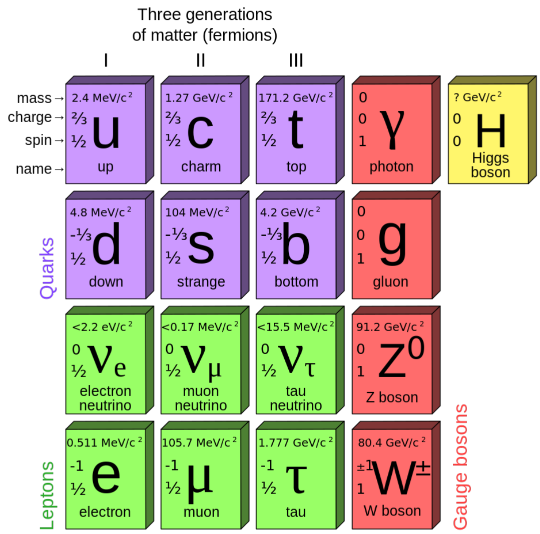
[24]he numbers of positively charged protons and negative electrons are always the same in an atom and so the atom is neutral. The elements can be understood then as a series of atoms with one proton and one electron (hydrogen), two protons and two electrons (helium), etc. In addition there are a number of neutrons in every nucleus (except for hydrogen). It was later discovered that the number of neutrons can vary between two atoms with the same number of protons and electron but as the neutron is electrically neutral it means that that atom has the same chemical properties and so it is not a different element.

been discovered that protons and neutrons are made up each of three smaller particles - so-called ‘quarks’. So far the much smaller electron has not been divided and it remains in that sense a ‘fundamental’ particle.

Another question that wasn’t explained until the 1970s is how protons remain so close to one another in the tiny confines of the nucleus. We all learnt in school that ‘like charges repel’. Since the protons all have the same positive charge, they ‘repel’ each other. Within the nucleus they are so close together that they are all subject to huge forces that try to push them apart. There must therefore be an equal force between them that balances this repulsion and holds them together in the nucleus - and this was named very mundanely the ‘strong’ force. The strong force is also responsible for holding together the quarks that make up the protons and the neutrons. (Two of the quarks in each proton or neutron have the same electrical charge which would otherwise repel each other).

The Standard Model and the Higgs Boson

These discoveries in high-energy physics have led to the development of what is now called the ‘Standard Model’ of elementary particles - a theory that attempts to explain the nature of sub-atomic particles and the forces that act upon them. It is best summarized by the diagram shown in the figure below. It shows the six quarks (including the up and down quarks (u and d) that form the protons and neutrons) along with the other lighter particles (the ‘leptons’) including the electron. In the fourth column are the gauge bosons or particle associated with the fundamental forces that act on the quarks and leptons. These include the photon that is the basic unit of light and the gluon that is associated with the strong force that holds the up and down quarks together in the proton and neutron.



The three particles in the model (up quark, down quark and the electron) that make up the atoms of the stuff we see around us are stable - that is they don’t disintegrate or change, But the module incorporates a number of other particles, that are not building block of atoms (the other four quarks and the leptons other than the electron). These particles mostly only exist for very, very short times after their production by a particle collision (in an accelerator like the LHS or, for example, in natural processes involving cosmic rays). Within the tiniest fractions of a second after they have been produced or created they ‘decay’ or change into one or more of the others in complex processes eventually leading to one of the stable particles.

And so alongside the up and down quark there are another four quarks given the somewhat bizarre names of ‘top’ ‘bottom’, ‘charm’ and ‘strange’ (t, b c and s). The word ‘quark’ was coined by Murray Gell-Mann, one of the scientists that first proposed their existence 1964. This initial theory was that there were three quarks and when he found a passage in James Joyce's *Finnegans Wake*

> Three quarks for Muster Mark!
> Sure he has not got much of a bark
> And sure any he has it's all beside the mark[25]

he settled on the spelling of the word. The pronunciation (rhyming with 'cork' rather than 'bark') he had chosen before he found the literary reference.[26] The top, bottom strange and charm quarks are produced in high energy collisions (such as those involving cosmic rays and in particle accelerators) but are short lived and decay to other quarks.[27]

Shown in the third row in the Standard Model are the neutrinos (Italian: little neutral one. The symbol is the Greek letter nu, ν) and were so named because they are electrically neutral and are the lightest of any of the particles that have any mass at all. They originate in nuclear reactions, radioactive decay and in the interactions between cosmic rays and matter, For this reason they are all around all the time. However, primarily because of the lack of electric charge and the tiny mass neutrinos do only interact with matter very weakly and can therefore pass through solid objects like ourselves and even the earth practically unimpeded. In fact, billions of neutrinos that have originated in the sun pass through our bodies every second with any noticeable effect on us![28] Alongside the electron there are two other similar particles, the mu or muon and the tau (again named after Greek letters μ, τ) that like the electron carry negative electric charge. Muons also exist all around us as they are generated when cosmic rays (e.g. protons originating in deep space) interact with the Earth's atmosphere. Because they can last for a relatively long time (their mean lifetime is 2.2 microseconds) before decaying to an electron and because they are travelling at almost the speed of light they can reach and penetrate the surface of the Earth.[29]

And finally the newly added Higgs boson completes the diagram. The existence of the Higgs boson is a long-standing prediction of the Standard Model. In 1964 three physicists proposed the existence of a force 'field' and an associated particle that would help to explain why some particles are heavier than others and some have no mass at all. The particle became known as the Higgs boson and because of the huge energy needed to create it artificially it remained undiscovered until last year [30]. On 4 July 2012, the ATLAS and CMS experiments at the Large Hadron Collider announced they had each observed a new particle in the mass range expected for the Higgs boson. Since then further experiments have measured some of its other characteristics and found them to be consistent with the theory. However, it remains possible that there may be more than one different types of Higgs boson[31].

It acquired the nickname, disliked by most physicists, 'God Particle' from the title of a popular science book in 1993. One

[25](James Joyce [1939]. *Finnegans Wake*. Penguin Books. p. 383 (1982 Edition)

[26]Murray Gell-Mann (1995). *The Quark and the Jaguar: Adventures in the Simple and the Complex*. Henry Holt and Co. p. 180

[27]`http://en.wikipedia.org/wiki/Quark` accessed on 1 May 2013

[28]`http://en.wikipedia.org/wiki/Neutrino` accessed on 1 May 2013

[29]`http://en.wikipedia.org/wiki/Muon` accessed on 1 May 2013

[30]`http://home.web.cern.ch/about/physics/search-higgs-boson` accessed 6 May 2013.

[31]`http://en.wikipedia.org/wiki/Higgs_boson` accessed on 6 May 2013

of the authors, Nobel prize winner, Leon M. Lederman, explained that the nickname does not derive from any idea that it is the most fundamental particle in any divine plan but that publisher would not allow the autors call it the 'Goddamn Particle' although that may have been more appropriate given the Higgs boson's elusive nature and the difficulty in discovering it![32].

As well as the search for the Higgs boson and the verification of the Standard Model, numerous other experiments investigating the fundamental nature of the physical universe we live in are being carried out at the LHC at CERN. The topics include the nature of 'anti-matter'[33], the search for 'dark matter' and processes shortly after the big bang. There are also experiments are aimed at more down-to-earth areas such as the effect of cosmic rays on cloud formation or biological effects[34].

Cost of the LHC

One of the issues that concerns anyone with even a passing interest in the LHC, particle physics or even science itself is the cost. The costs of construction and the development of the technology at the LHC are indeed high and are estimated to have run to approx. €3.1 billion.[35] The annual budget to support a staff of 2,400 and 10,000 visiting scientists ran to just under €1 billion in 2012 [36]. While these figures might have seemed to have been really gigantic before the onset of the global economic crisis in 2008 they might not seem to be so enormous when put beside the sums involved in the bail-out of banks - even the banks in a country as small as Ireland. Incidentally, Ireland is not one of the 20 'member' states that fund CERN. Nor is it one of 36 countries with 'co-operation agreements'. It is in the third rank of 18 other states that have 'scientific contact' with CERN.[37]

It is instructive to also compare the amounts of money spent on the LHC with military expenditure. For example, the annual military budget of the Czech Republic, a CERN member state and nowadays also a member of NATO (but nonetheless hardly a global military force), is estimated to be over twice the annual budget of CERN.[38]

The capital cost of the LHC does not seem quite so gigantic either when put against the cost of the latest addition to the US Navy, the aircraft carrier *Gerald R Ford*, due to be launched in 2013. This single ship has an estimated price tag of US$12.8 billion - over three times the cost of building the LHC.[39]

What then of David King's argument, mentioned earlier, that countries like Britain should divert funds from the LHC and use them to fund climate change re-

[32]Leon M. Lederman and Dick Teresi (1993, reprint in 2006). *The God Particle: If the Universe is the Answer, What is the Question?*. Boston: Houghton Mifflin Company.

[33]In the Standard Model all charged particles have an 'anti-particle' which have the opposite electric charge to the normal particle. For example the anti-particle of the electron (charge = -1) is the 'positron' or 'anti-electron' with a charge of +1).

[34]A list of the experiments at the CERN can be found on `http://home.web.cern.ch/about/experiments` accessed o 6 May 2012

[35]`http://en.wikipedia.org/wiki/LHC` accessed on 6 May 2013

[36]`http://press.web.cern.ch/facts-and-figures/budget-overview` accessed on 6 May 2013

[37]`http://home.web.cern.ch/about/member-states` accessed on 6 May 2013

[38]`https://www.cia.gov/library/publications/the-world-factbook/geos/ez.html` accessed on 6 May 2013

[39]Ronald O'Rourke, Navy Ford (CVN-78) Class Aircraft Carrier Program: Background and Issues for Congress, Congressional Research Service, 7-5700, RS20643, April 2013

search? Is he not falling into the trap that the establishment, of which he is of course a part, always set for us? Why should we have to settle for one or the other? Can we not have research into the fundamental nature of our universe and research into offsetting the impending disaster that global warming may cause? King's thinking embodies the same kind of argument that revolutionary socialists reject when we fight against hospital cuts and simultaneously defend the funding of the arts. These are Hobson's choices that we would not need to make in a society where there was real democratic control of resources.

It also seems strange that a scientist like King would argue against carrying out fundamental research. He must surely acknowledge that all science is actually interconnected. The fundamental research that was carried over a decade or even a hundred years ago can become the basis for the technologies today. For example the then esoteric theory of electromagnetism developed by James Maxwell in 1865 is the basis for all generation of electricity - including the clean energy produced in wind farms today. The world would be a different place today if scientists like Maxwell had been halted in their research because there was no obvious application for electromagnetism in the age of the gas light and steam engine.

Implicit too in King's argument is the idea that the problems caused by climate change can be met with the current knowledge of the fundamental sciences. There seems too to be an assumption that diverting the scientific budget for a year or two or maybe even a decade will crack the nut. As Owen McCormack argued in the first edition of this journal the fight against climate change is much bigger than that and will necessitate 'stopping capitalism from consuming the planet, and ending the inequalities at its heart.'[40] Furthermore, the new science and technological advances that may come from research such as done in the LHC may well play a crucial role in the technological challenges, including climate change, facing humanity in the future. It is not always predictable where new breakthroughs in science will have their application. For example, the discovery by the German physicist von Laue in 1912 of x-ray diffraction [41], a technique for investigating the properties of solid crystals, was used to determine the crystal structure of DNA forty years later [42]. All the advances in medicine and biology that have since flowed from that discovery could surely not have been predicted by von Laue when he first discussed the idea of scattering x-rays by a crystal with a colleague on a stroll in the English Garden in Munich in 1912!

Finally, fundamental research in particle physics and cosmology, in particular, have informed our ideas on the nature of matter, energy, the universe and therefore ourselves and our place in nature. As materialists it would seem very odd if socialists were to argue that such an understanding was not required as we fight to sweep away the old superstition and struggle to end the age of cant![43]

[40]Owen McCormack, 'The age of extremes: new developments in climate change', *Irish Marxist Review Issue 1*, p. 50.

[41]`http://en.wikipedia.org/wiki/X-ray_diffraction` accessed 6 May 2013

[42]`http://en.wikipedia.org/wiki/DNA` accessed 6 May 2013.

[43]`http://en.wikipedia.org/wiki/Internationale` accessed 6 May 2013