THE HIGGS BOSON
HOLY GRAIL OF PARTICLE PHYSICS

Nigel Lockyer, TRIUMF, 4004 Wesbrook Mall, Vancouver, BC Canada V6T 2A3

Abstract

The most sought after particle in history is the Higgs Boson. Arguably, the Large Hadron Collider (LHC) at CERN has been built to find the Higgs. Some kind of Higgs mechanism is needed in the Standard Model to give mass to the intermediate vector bosons, the carriers of the weak force. The same mechanism gives mass to the quarks and leptons as well. An elementary introduction to the Higgs Boson is presented.

INTRODUCTION

There are several motivating questions that drive research in particle physics and for more than half of these it can be argued the Higgs boson sheds some light on the question.

1. Are there undiscovered new symmetries or laws in nature?
2. Are there extra dimensions of space? (small or large)
3. Do all the forces become one?
4. How can we solve the mystery of Dark Energy?
5. What is Dark Matter?
6. Where is all the anti-matter?
7. How to combine quantum mechanics & gravity?

Items 1) and 2) motivated by new physics to stabilize Higgs mass calculation-no fine tuning assumption. Item 3) Hints exist & needs spontaneous symmetry breaking. Item 4) Higgs may be part of the puzzle. Items 5) 6) require experimenters to get more data since theory cannot lead. Item 7) String theory has much to say about this since it is the only theory to include gravitational interactions and particle physics.

In this paper we'll discuss: What is the Higgs Boson? What is the Higgs Mechanism? Why are weak interactions weak? Connections to Nuclear Physics & Astrophysics? Higgs Search Status at Tevatron and a few words about the ILC as a Higgs Factory.

Peter Higgs is a theoretical physicist from the University of Edinburgh. He did his seminal work over 40-years ago. He was motivated by the work of Schrieffer and Nambu amongst others, who had been studying superconductivity. It was recognized that the Higgs field was a form of superconductivity in vacuum, a relativistic quantum fluid that fills all of space.

In a superconductor, Cooper pairs form a condensate which breaks the electromagnetic gauge symmetry and expels magnetic fields from inside the superconductor, a phenomena called the Meisner Effect. One interpretation of the Meisner effect is that the electromagnetic fields in the superconductor are short range and therefore cannot penetrate the surface more than a short distance. In an ordinary metal, we know electric fields inside the conductor are zero due to a rearrangement of the electric charges on the surface of the conductor. However, magnetic fields can fully penetrate a conductor. In a superconductor, the photon becomes massive and consequently has a short range, inversely proportional to the mass.

The Higgs mechanism is a form of superconductivity in vacuum. The Higgs field fills all space and prevents the weak force from propagating over infinite distance. In the simplest case, the Higgs field consists of 2 neutral and 2 charged components. When the Higgs acquires a non-zero vacuum expectation value, the Higgs field then has a non-zero value throughout space. The value is given in the standard model as 246 GeV. Three of the fields, the two neutral and one charged field mixes with the three W and Z bosons, giving them mass, and the other remaining field is the scalar Higgs boson. The weak force range is inversely proportional to the mass of the W and Z bosons.

Now for a few simple definitions to set the stage for further discussion. A particle is a disturbance in a field. An example of a field, such as a temperature field, is a number at every point in space that describes the temperature at that point. If one number describes each point, it is called a scalar field. If two numbers are required, such as with a wind field or a magnetic field, where you need a number and a direction, it is a vector field. The Higgs field is a neutral scalar field that fills the entire universe. Particles travelling through the universe interact with the field and become massive. Importantly, the W and Z become massive and the photon must have a mass identical to zero in the standard model.

We wish to introduce the concept of spontaneous symmetry breaking in a non-rigorous manner. Firstly, symmetry is a concept we are all familiar with, especially in art. M.C. Escher is a good example. It is however more precisely defined in physics and this leads to some confusion. Often, non-scientists think a snow-flake has a great deal of symmetry (6-fold) and yet steam does not. However, if we define a perfectly symmetric system as one where every direction for example, is identical, then steam is more symmetric than a snow flake. Therefore, steam, after it cools, loses symmetry. The original symmetry is broken.

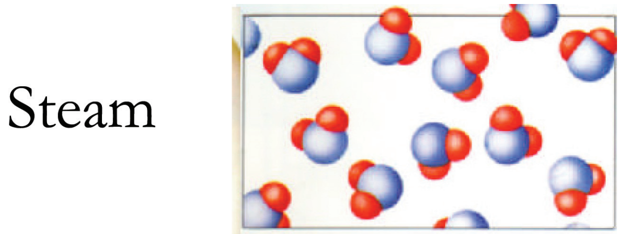

Figure 1: Steam is fully symmetric.

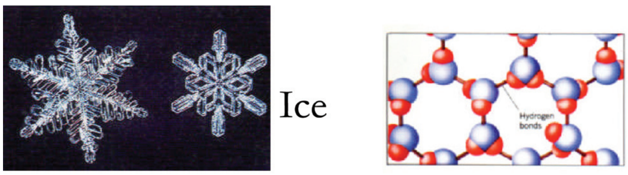

Figure 2: The snowflake has less symmetry than steam.

Iron is an excellent example. Above the critical temperature, iron is non-magnetic. Below the critical temperature, the spins of the iron atoms (actually domains) spontaneously align, and the symmetry is decreased. Above the critical temperature, the spins are not aligned, and iron is in a state of greater symmetry.

In the example with the Mexican hat potential, the system starts out in a fully symmetric state when the ball (or Higgs Boson) is at the top of the hat. The ball is in a state of unstable equilibrium and will fall down eventually. When the ball rolls down, a random direction is chosen (or in the case of the Higgs a random phase is chosen), which spontaneously breaks the symmetry. This ball rolling down the hat happens when the universe cools for the massive Higgs boson, in which case the Higgs rolls down a potential. A very similar potential describes the breaking of gauge symmetry in a superconductor when the Cooper pair condensate forms.

Ferromagnetism above the Curie temperature is spatially invariant and there is no magnetic field in space. Below the Curie temperature, the symmetry is spontaneously broken, and there is a magnetic field created in space. This is called a phase transition. One can demonstrate this effect by heating an iron nail with a blow torch. Once red hot, the nail is above the Curie temperature and will not stick to a simple bar magnet. As the nail cools, the spins align at the critical temperature, the symmetry being spontaneously broken, a net magnetization is created and the nail sticks to the magnet.

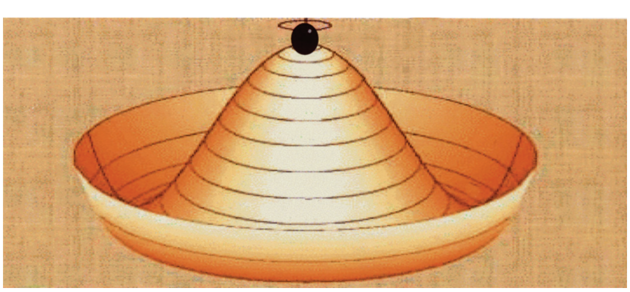

Figure 3: Mexican hat potential. The ball rolls down into the brim breaking the initial “symmetric state”.

This is in analogy to the universe cooling, and at the critical electroweak temperature, there is a phase transition and the electroweak symmetry is broken and the Higgs field is created in space. The electroweak phase transition occurs about one pico-second after the Big Bang. This is the time (or energy or temperature) scale being explored by the Large Hadron Collider (LHC). Above this temperature there is no Higgs field, and below this temperature there is a Higgs field. The electroweak symmetry breaks into electromagnetic and weak fields (in analogy to the rotational symmetry breaking in the ferromagnetism example). The W & Z gain mass and have finite range whilst the photon remains mass-less and has infinite range.

When the universe was created, all four forces, gravity, electromagnetic, weak, and strong force are thought to be identical. The universe was fully symmetric. However, as the universe expanded and cooled, at the temperature of the Planck scale, gravity breaks away from the other three forces, and then at the Grand Unification scale of 10^{16} GeV, the strong nuclear force and the electroweak force go through a phase transition and separate. Observing the spontaneous electroweak symmetry breaking at the LHC will give us more confidence we are on the right track for unification (maybe).

Why are we excited about the LHC? The LHC will substantially increase the energy scale we study in particle physics by a factor of seven. This is a big jump and we cannot possibly predict what will be seen. The LHC is an exploratory machine. Importantly, if the idea of electroweak symmetry is correct, the LHC will prove it and thus explain why the weak interactions are weak.

The Higgs is different. All matter particles are spin-1/2, while all forces are carried by particles with spin-1. Higgs particles are spin-0. The Higgs is neither matter or a force carrier. The Higgs is its own antiparticle. The Higgs is just different. It would be the first fundamental scalar observed. All extensions of the standard model contain scalar fields, such as the inflaton of inflation or the radion of extra dimensions. Discovering the first fundamental scalar will indicate we are perhaps on the right track with these other ideas. The Higgs will also be a powerful probe of new physics. The standard model constrains the couplings to the quarks, and measuring those couplings precisely will be a powerful test of the standard model and whether new physics is leaking in. In principal, the Higgs will couple to other scalars in any broader theory, and this could show up in the couplings.

It is interesting to note the Higgs mechanism does not give the proton or neutron most of their mass. Most of the mass of the proton or neutron comes from the chiral symmetry breaking in QCD. However, the mass of the quarks is important because it is the Higgs interaction that determines which of the up or down quarks is heavier. The proton (uud) is lighter than the neutron (udd) because the mass of the down quark is greater than that of the up quark. If the quarks had equal mass, the proton would be slightly heavier than the neutron because of its charge, and the proton would decay to the neutron. Furthermore, since the electron would be massless without the Higgs mechanism, the Bohr radius of the electron, inversely proportional to mass, would be infinite and there would be no chemistry. The lightest nuclei would be neutral and atoms would not exist. The universe would be quite different. The Higgs is very important to how we understand our visible universe.

The best experimental limits on the Higgs come from the Tevatron. Figure 4 shows the exclusion plot using 3 fb^{-1} of data, CDF and D0 combined. The data are sensitive enough to just about exclude masses around 170 GeV/c^2. The lower mass range, 115-150 GeV/c^2, has sensitivities about three times the standard model cross section.

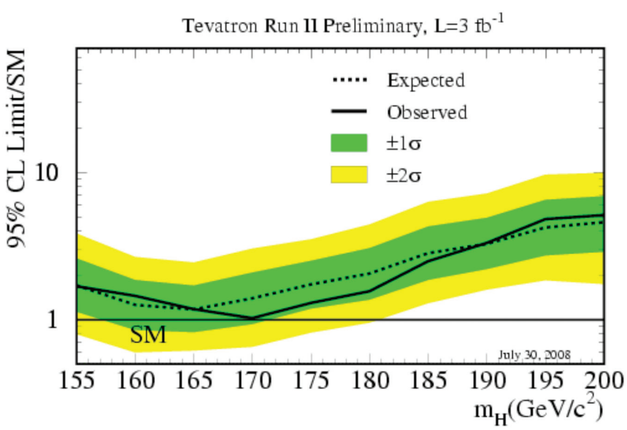

Figure 4: Exclusion plot for SM Higgs boson.

There are several systems in nature that exhibit phenomena that is similar to superconductivity, the Higgs mechanism being just one such system. A well known example is Helium-3, which is a p-wave superfluid at low temperatures. The system is an example of fermionic atoms, not electrons as in metals, that exhibit pairing properties.

Another example, less dense that helium-3, is a quantum fermionic gas, such as Li-6 gas. When trapped and cooled below a critical temperature Tc, the system exhibits superfluid vortices. If the system is placed in an external magnetic field, the inter-atomic attraction can be adjusted, hence varying the strength of the coupling. This makes it possible to create cold Fermi gases with a high Tc. Figure 5 shows superfluid vortices in a quantum gas [1].

In the nucleus, neutrons can pair with neutrons and protons can pair with protons. Since the interaction between nucleons is strong, it is not necessary to cool the nucleus in order to observe super-effects. Therefore in nuclei with an even number of protons, *superconductivity* behaviour is observed and nuclei with an even number of neutrons *superfluid* behaviour is observed. This is exhibited by the excitation energy-gap of about one MeV in even-even nuclei.

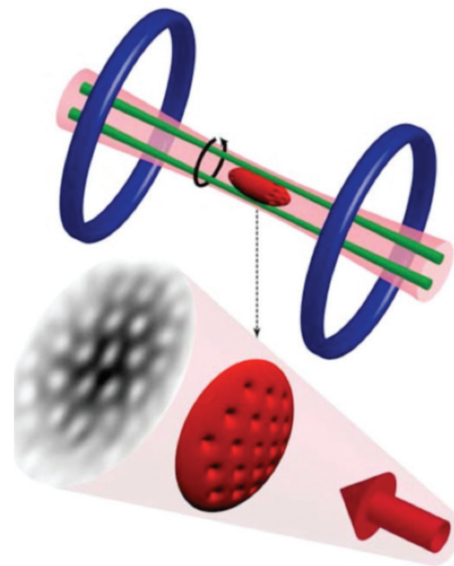

Figure 5: Superfluid vortices in trapped ultra cold atoms[1].

In even-odd nuclei, the excitation energy is a factor of ten less. This discovery was made one year after the discovery of BCS theory.

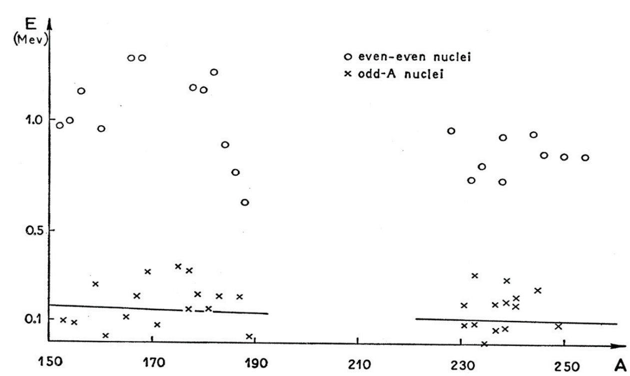

Figure 6: Excitation energy-gap in even-even nuclei compared to odd-mass nuclei[2].

Neutron stars are very interesting laboratories for many studies. The crust contains neutron-rich nuclei in a sea of neutrons. Initially, once the neutron star is born, the temperature of the star is too high to allow a superfluid, but quickly the neutrons in the crust form an s-wave superfluid. In the core, the neutrons may form a p-wave superfluid and the protons an s-wave superconductor. These condensates impact the cooling of the neutron star. It is known that roughly in the first 10^6 years, cooling is primarily due to neutrino emission. The processes are neutron decay and electron capture on protons. If the neutrons or protons are paired, extra energy is needed to break the Cooper pairs and therefore superfluid/ superconducting neutron stars cool slower.

In some X-ray bursts in accreting neutron stars, it is possible to observe the cooling of the crust in real-time. The

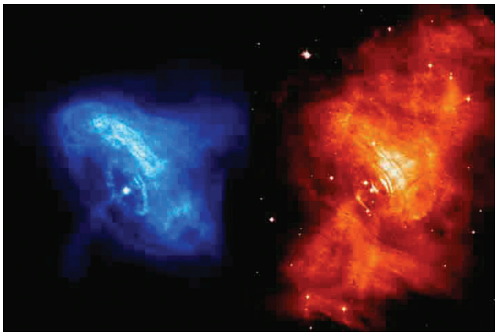

Figure 7: Crab pulsar in X-ray and optical: Superfluidity/superconductivity impacts cooling of neutron stars.

light curve time constant is affected by whether the crust is a superfluid. In pulsars, there is angular momentum stored in superfluid vortices in the crust in a similar manner to a superfluid that has been rotated. As the neutron star rotation period slows down, it is possible for these vortices to transfer their angular momentum to the stars rotation. This suddenly increases the rotation rate of the star, and these spin ups are observed as glitches in the period[3].

CONCLUSION

Particle physicists at Fermilab and CERN are in hot pursuit of the Higgs boson. If found it will be the last missing particle in the standard model. The Higgs boson will be the first fundamental scalar observed and will give credence to proposed models beyond the standard model that have scalar fields, including inflation. The precision study of the Higgs may reveal new physics beyond the standard model. The Higgs mechanism is one of several phenomena in nature that connects to superfluidity and superconductivity. The International Linear Collider may be the ideal new machine to explore the properties of the Higgs.

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