

What Gives Matter its Mass?

The Higgs Boson and the Standard Model of Particle Physics

Lynn Punnoose

Scientists and philosophers have labored since ancient times to reduce matter to its basic constituents and to determine its fundamental properties. This drive to understand the universe by simplifying it is exemplified by the Standard Model of particle physics, which describes the particles that make up matter and the forces that act upon them. While most of the particles in the Standard Model have been observed and described, the one particle that gives matter that property which many of us have supposed inherent –mass–has not yet been “seen.” This particle is called the Higgs boson, and the field in which it acts the Higgs field.

The Standard Model includes three of the four known forces in nature: electromagnetic, nuclear weak and strong nuclear forces. Gravity is not included in the model because unifying the Standard Model (quantum physics) with gravity—and general relativity—requires a plausible explanation of the vast disparity in “energy scales” between the two.¹ While the gravitational, strong, weak, and electromagnetic forces display similar strengths at particle energies of 10^{16} to 10^{18} GeV (billion electron volts), the energy scale for the unified electromagnetic and weak forces (electroweak force) is only 100 to 200 GeV.^{1,2}

The three forces presented in the model act upon particles through force “carriers”³ called bosons. In other words, the effects of any of these forces can be thought of as being transmitted not through a field, but rather through particles.⁴ The Heisenberg uncertainty principle, which states that one cannot accurately measure both the position and the momentum of a particle at the same time, supports this idea of force being transported from one point to another by particles that can exist for very short periods of time.⁵ A corollary of the Heisenberg uncertainty principle is that energy cannot be measured accurately during a very short specified time interval. The resulting large error in measurement allows for the “nonconservation” of energy and for this energy to contribute to the



creation of a particle—the force carrier. The mass of the particle is directly proportional to the energy required for its creation and inversely related to the time interval during which it can exist. Therefore, more massive bosons can carry their respective forces only for short times and over short ranges.⁵

However, the various bosons are not the only particles represented in the Standard Model. The forces carried by the bosons act on quarks and leptons, the building blocks of matter. The leptons, of which the electron is one type, are elementary particles upon which the strong nuclear force has no effect. There are six leptons: the electron, muon and tau particles and their associated neutrinos. The range of masses for these particles is quite large. For example, the mass of the muon is 200 times that of the electron.⁶ In addition to the leptons, six quarks are also included as fundamental particles of matter: the up, down, charm, strange, top and bottom quarks. The top quark, the heaviest of the six, is approximately 350,000 times more massive than the electron.¹ Each of the leptons and quarks also has an antiparticle, which is a particle with identical mass and opposite charge.⁷

The ultimate goal in particle physics is to find the one model that unifies all four of the forces present in nature with Einstein's theory of general relativity. Perhaps the first step in this direction was the attempt to unify the electromagnetic and weak forces into one, called the electroweak force. The quantum electrodynamic theory (QED), developed by Richard Feynman, Sin-itiro Tomonaga, and Julian Schwinger in the 1940s, 10 postulated that the massless photon is the "messenger particle"⁴ that transmits the electromagnetic force, which acts as an attractive force between opposite charges and a repulsive one between like charges. The electromagnetic force weakens quadratically with increasing distance between charged particles.

The weak force, in contrast to the electromagnetic force, acts between particles by means of not one, but three bosons. Since the force acts only over a short range, these force carriers are correspondingly massive. In beta decay, for example, the W^- boson acts as an intermediary in the decay of a neutron into a proton, an electron and an anti-neutrino, or more specifically, the conversion of a down quark into an up quark with the release of an electron and an antineutrino. Similarly, conversions of up quarks into down quarks require the action of W^+ bosons.¹¹ A third boson, which mediates another kind of interaction called neutral currents, was discovered by the early 1980s. This would be the photon's counterpart among the weak force bosons. Neither of the W bosons fit the bill, because they both have charge and the photon has no mass although it is neutral. The Z^0 boson, on the other hand, was found to have a large mass,

similar to the W bosons, but zero charge. This particle mediates the collision of a neutrino and an up quark, in which the weak force is involved. While no new particles are generated in this collision, the Z^0 boson is responsible for transmitting the force from the neutrino to the up quark (which is part of a neutron or a proton).¹¹

The observed Z^0 boson and the photon are results of the mixing of two neutral force carriers of the electroweak force. Sheldon Glashow, Abdus Salam, and Steven Weinberg, who were awarded the Nobel Prize for their model of the electroweak force, theorized that the neutral bosons— B^0 and W^0 —in addition to the charged W^+ and W^- bosons were responsible for carrying the electromagnetic and weak forces between particles.¹²

Unlike the electroweak force, the strong interaction between quarks acts to draw them together and obtain a "color" of white,⁸ creating hadrons such as neutrons and protons. According to the quantum chromodynamics theory (QCD), each quark can have one of three different "colors," in addition to its electrical charge. A proton, for example, is made of two up quarks and one down quark, while a neutron consists of two down and one up quarks. Eight gluons are involved as carriers of this force. Each of the gluons, which carry two colors, are responsible for changing the color of the quarks with which they interact. The energy required to separate two quarks is very high, since the strong force increases in magnitude as distance between the particles grows. Even before the quarks present, say, in a proton or neutron, detach from each other, enough energy has been created for the generation of a quark and an anti-quark. It is thus very difficult to observe a free quark.⁹

However, the large disparity in masses between the bosons disrupted not only an aesthetic requirement for symmetry in the universe¹³, but also the principle of gauge symmetry. Gauge symmetry requires that the measurement of a particle's or a wave's position remain unchanged regardless of a change in its phase, or where in space time it originates. This theory is successful in predicting the photon and its characteristics.¹² However, the large masses of the W^+ , W^- and Z^0 bosons break the gauge invariance and thus the model for the unification of weak and electromagnetic forces which is based upon it.¹³ In particular, theorists found that the theory predicts the probability of the two W bosons colliding to be greater than one, a statistical improbability.²

That is, until the Higgs particle enters the picture. Weinberg theorized that the bosons begin with no mass and only gain it upon interaction with the Higgs field. The gauge symmetry is thus preserved for the electroweak force and is "hidden" by the Higgs field, which gives it mass.¹⁴ Mass is not

thought to be an inherent property of matter, but rather a characteristic acquired, like velocity, through interaction with a force.¹⁴ The precise mechanism by which the field accomplishes this task is unknown. The Higgs field is a scalar one—that is, the force acts on particles irrespective of their spin, or direction.¹ It is believed that massless particles—both matter particles and force carriers—“eat”² the Higgs boson and gain mass. However, the interactions of quarks and leptons with the Higgs boson require the presence of constants so that their masses can be calculated. Interestingly, for the top quark, the value of this parameter is almost one. This, in addition to the great mass of the top quark, suggests that it has a significantly different role in the Standard Model than do the other quarks and leptons.¹⁵ The force carried by the Higgs boson, postulated to be the fifth force present in nature, interacts with different particles to different degrees, thus giving each one a different mass.² The reason for this lack of uniformity is unknown. In addition, the cause of the Higgs boson’s mass itself has not been determined, although it may be largely due to the Higgs force.²


The simplest hypothesis for the Higgs mechanism, which unifies the electromagnetic and weak forces, describes only one Higgs field. However, a unification scheme that includes the strong force, called the SU(5)², requires additional force carriers and forces¹—and a second Higgs field to account for the masses of these new bosons. A fundamental unification theory, supersymmetry, takes gravity into account as well. This theory postulates the existence of many more particles that gain mass from their interactions with new forces at energies much lower than 10^{16} GeV.¹ Five of the new particles proposed in the theory of supersymmetry are Higgs bosons.¹⁶ The particles of the Standard Model would interact with these hypothetical particles to acquire their masses.¹ It is important to emphasize, however, that both the model postulating one Higgs boson and the more complicated ones have yet to be proven by experimental evidence.²²

The Higgs boson must be found and its mass determined. Experiments to find the boson at the Large Electron Positron (LEP) Collider in CERN, the Center for Nuclear Research in Geneva, Switzerland, involved the collisions of electron and positron beams at energies of 200 GeV. The energy resulting from these collisions was expected to be sufficient for the generation of one Z^0 boson and a Higgs boson. While these bosons would not be directly observed, scientists looked for their decay particles, quarks and antiquarks, in four streams of particles observed by detectors. These detectors consist of many sensors and scintillation counters, among other materials, which record

information about collisions such as particles’ trajectories, energies, and charges.^{16, 17} However, detectors must first decide which collisions have produced significant results worth recording. If the results of a collision meet previously set conditions, such as the production of a certain number of streams of particles, or a high amount of energy, the detector records information about that particular interaction.¹⁷

The Higgs boson specifically decays into bottom and antibottom quarks, and researchers at CERN searched for evidence of these streams in the aftermath of electron-positron collisions.¹⁸ But data from the four experiments carried out so far—ALEPH, DELPHI, L3 and OPAL—showed no evidence of the boson. When the researchers increased the colliding beams’ energies to 103 GeV each¹⁹ and then examined the tracks left by particles formed in the collisions, they found the characteristic decay products of the Higgs boson. Experiments last September and October determined that the mass of the boson is 115 ± 1 GeV, or at least not less than 113 GeV. The probability that the tracks, which researchers believe are left by the Higgs boson decays, arose from other background events is almost 1 in 1,000.¹⁸ Although this seems to be a rigorous standard, in physics scientists must gather enough data to reduce this probability to less than or equal to one in 105 before the data will be accepted as definitive evidence of the Higgs boson.²⁰

However, the particle accelerator at CERN has been shut down so that work on the Large Hadron Collider (LHC) can be completed by 2005. More information on the Higgs boson must therefore come from Fermilab in the United States, currently housing the most powerful accelerator in the world—the Tevatron, which can accelerate particles to energies of almost 1TeV (trillion electron volts)²¹ and which, unlike the LEP, uses colliding beams of protons and antiprotons. However, the LHC, when it is completed, will be able to accelerate particles to seven times this energy.¹⁸ Thus, if the Higgs particle is not found at the Tevatron, and if it exists, it will most likely be discovered at the Large Hadron Collider, where beams of energy sufficient for its generation can be made to collide.

The Higgs boson represents not the completion of the Standard Model but a road to its improvement. Scientists need to determine not only the physical characteristics of this particle, but also its role in particle physics. They must also develop and test models that include all four known forces of nature, unlike the Standard Model. Finding the Higgs Boson is thus one step of many in determining how matter is formed, and through this, how the universe works. 

Acknowledgements

I would like to thank Professor Christoph Paus of the Physics Department for his guidance with this article and for his explanations of the theory behind the Standard Model.

References

- Weinberg S. A. “Unified Physics by 2050?” *Scientific American* 1999; 281: 68–75.
- Veltman MJG. “The Higgs Boson.” *Scientific American* 1986; 255: 76–84.
- Watkins P. *Story of the W and Z*. Cambridge: Cambridge University Press, 1986: 19.
- Lederman L. *The God Particle: If the Universe is the Answer, What is the Question?* Boston: Houghton Mifflin Company, 1993: 277.
- Watkins, P. *Story of the W and Z*, 18–20.
- Online glossary for particle physics. <http://zebu.uoregon.edu/~js/glossary/leptons.html>
- Lederman, L. *The God Particle*, 174.
- Collins GP. “Fireballs of Free Quarks.” *Scientific American* 2000; 282: 16–18.
- Lederman, L. *The God Particle*, 336.
- Watkins, P. *Story of the W and Z*, 46.
- Lederman, L. *The God Particle*, 325–328.
- Watkins, P. *Story of the W and Z*, 53–55.
- Lederman, L. *The God Particle*, 331.
- Ibid. Lederman, 369–370.
- Liss TM, Tipton PL. “The Discovery of the Top Quark.” *Scientific American* 1997; 277: 54–59.
- Fermilab Web site. http://www.fnal.gov/directorate/public_affairs/higgs/higgs_fnews.html
- Lederman, L. *The God Particle*, 248.
- Riordan M, Rowson PC, Wu S.L. “The Search for the Higgs Boson.” *Science* 2001; 291: 259–260.
- Morton O. “CERN Gives Higgs Hunters Extra Month to Collect Data.” *Science* 2000; 289: 2014–1015.
- Seife C. “CERN’s Gamble Shows Perils, Rewards of Playing the Odds.” *Science* 2000; 289: 2260–2262.
- Fermilab Web site. http://www.fnal.gov/pub/hep_descript.html
- Paus, Christoph. Personal Communication.