The Standard Model

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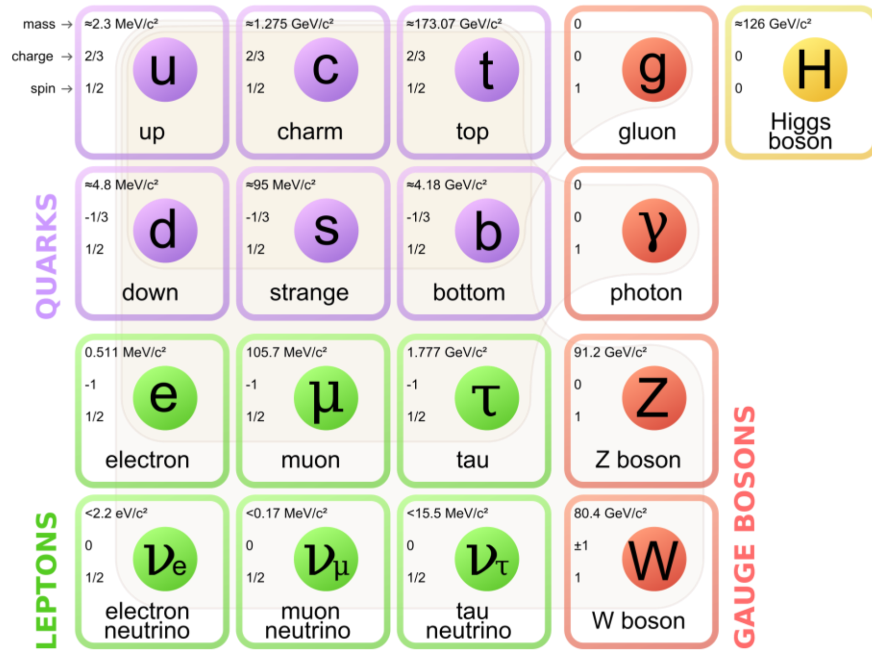
The Standard Model

The Standard Model of elementary particle physics provides the underlying theory for the three fundamental forces observed at microscopic scales: the electromagnetic interaction (electromagnetism), the weak interaction, and the strong interaction. Quantum electrodynamics (QED), Glashow-Weinberg-Salam theory (GWS), and quantum chromodynamics (QCD) are the three corresponding theories of the forces, respectively. The fourth fundamental force observed in nature, gravity, is not treated in the Standard Model as it is too weak to be detected in particle physics experiments. The Standard Model has lasted through precision tests for around forty years.

The Standard Model predicts that particles come in two types: *fermions*, with half-integer intrinsic angular momentum (spin) and obey Fermi-Dirac statistics, and *bosons*, with integer spin and obey Bose-Einstein statistics. All particles have antiparticles with reversed electric charge and color, which in occasional cases is the particle itself. An array of the elementary particles of the Standard Model is shown below.



On the bottom left are the *leptons*, which have spin ½. Of these particles, the electron, muon, and tau all have electric charge -1, while their corresponding neutrinos shown below them are electrically neutral. The leptons do not carry color and thus do not interact via the strong force.

At the top are *quarks*, which are also all carry spin ½. The top row (up, charm, top) of quarks all have electric charge ⅔, while the bottom row have charge -⅓. A particular quark may have one of three possible colors (red, green, or blue). The strong interaction, or color force, dictates that all observed particles that interact via the strong force (*hadrons*) are color neutral; that is, either all three quark colors are present, or a color and its anticolor are present. Therefore, the observed hadrons are all either *baryons* (composed of three quarks), *antibaryons* (three antiquarks), or *mesons* (a quark and an antiquark). Since the proton has two up quarks and one down quark, while the neutron has two down quarks and one up quark, they are both considered baryons.

The top 4 bosons down the right are known as *gauge bosons,* because their prediction in the theory is related to a mathematical phenomenon known as gauge symmetry. The gauge bosons all have spin-1 except for the Higgs boson, which has spin-0. The gluons and photons are massless and mediate the strong and electromagnetic forces, respectively, while the $W^{\pm}$ and Z^0 bosons are massive and mediate the weak force. The Higgs mechanism gives rise to the masses of the W and Z bosons, as well as the Higgs boson itself.

The interactions conserve the kinematic properties of total energy, linear momentum, and angular momentum as well as electric charge. Also conserved are two important quantities: baryon number, which is assigned as a 1 for each baryon and -1 for each antibaryon, and the individual lepton numbers, i.e. electron number, muon number, and tau number. Electron number, for example, is 1 for electrons and electron neutrinos, and -1 for antielectrons (also known as positrons) and electron antineutrinos. There is an approximate symmetry of flavor: strong and electromagnetic interactions cannot, for example, change an up quark into a down quark. The weak interaction is the only force capable of changing the flavors of quarks.

This means that, in general, a particle will decay to the lowest mass state allowed by the conservation laws. Consequently the lightest baryon, the proton, is stable; conservation of electric charge and lepton number make the electron and electron neutrino stable. The Standard Model predicts a rather strange behavior known as neutrino oscillations, in which the observed neutrinos are actually mixed states of the three neutrinos (electron, muon, and tau), so a later measurement would return different probabilities of being a particular type of neutrino than an earlier measurement would.

Historical Background

Atomic Understanding

The word atom comes from the Greek word ἄτομος, or atomos, meaning indivisible. The idea of an atom originated from Greek philosophers Leucippus and Democritus, who believed that the world consisted of an infinite number of indestructible atoms. In developing this theory, they addressed how change arises. If something could not come from nothing and change was not illusory, then there must be unchanging particles that rearrange to produce change, or indivisible atoms.

Two thousand years later, John Dalton proposed the concept of indivisible atoms combining to form chemical elements, which could then combine to form more complex compounds. In 1897, J. J. Thomson showed that atoms did have constituent parts with his discovery of the electron, thus truly beginning the development of the Standard Model. Thomson was investigating the cathode ray, an electron beam that constructed by applying high electrical voltage to a partially evacuated glass tube with electrodes on each end. One of the electrodes is a cathode and the other is an anode, causing electrons to flow from the anode to the cathode. Thomson resolved the mystery surrounding these electric currents when he measured the mass of the cathode ray, which turned out to be lighter than hydrogen. This experiment introduced the concept of subatomic particles, and more specifically, electrons.

From this, Thomson came up with his plum pudding model of the atom, in which electrons were the building blocks of atoms and resided in a pudding of positive charge. Ernest Rutherford disproved this concept in 1911 by shooting a beam of alpha particles onto a thin sheet of gold foil. According to the plum pudding model, most of the alpha particles should have passed through the gold foil with minute deflections. However, in reality, a few of the alpha particles were deflected backwards at large angles, suggesting that there was a concentrated positive charge at the center of the atom. This scattering phenomenon is now called Rutherford scattering. Rutherford later named positively charged particles in the nucleus “protons”. He also proposed a neutral particle in the nucleus, called the neutron, although these were not formally discovered until 1932.

Particle Zoo

In 1928 the Dirac equation gave the first indications of “antiparticles.” Paul Dirac was attempting to unify quantum mechanics and special relativity and created an equation that generalized Schrodinger's equation, describing the conservation of energy on a quantum level to allow for relativistic mechanics. However, the equation allowed for two solutions, which gave electrons positive or negative energy, and suggested that electrons can jump between positive and negative energy states, a phenomenon that had not been observed. Eventually, Dirac resolved this by introducing the positron--a subatomic particle with the same mass as an electron but an opposite, positive charge. In 1947, Ernst Stueckelberg proposed that positrons are electrons propagating backwards in time, and as such have a positive charge but with otherwise identical properties to electrons. Richard Feynman also proposed this in his theory of Quantum Electrodynamics, so this concept is now called the Feynman-Stueckelberg interpretation.

Carl Anderson formally discovered the positron in 1932, using a Wilson chamber, or a cloud chamber. In 1912, Charles Wilson invented the chamber, which consists of a sealed chamber with air and water vapor inside. Water is left inside the chamber until it evaporates, saturating the air. The pressure is then lowered, cooling the air and causing the water vapor to condense onto charged particles passing through the chamber, producing droplets that leave a trail. Anderson found positrons in cosmic rays, which he passed through a cloud chamber with a surrounding magnet; the positrons left trails that matched those of electrons, but in an opposite direction. Since then, cosmic rays have been used to observe a myriad of particles including muons, kaons, pions, and neutrinos.

Around the same time as Anderson, Wolfgang Pauli and Enrico Fermi proposed the idea of a neutrino. Neutrinos arise from beta decay, in which a nucleus emits beta particles (electrons or positrons). However, releasing electrons or positrons alone does not conserve energy in beta decay. To resolve this, in 1930, Pauli proposed the neutrino, a neutral particle about as light as an electron, which even he admitted was an "incredulous" proposition. Three years later, Francis Perrin showed that the mass of the neutrino must be zero or extremely small compared to that of an electron. Fermi further developed beta decay using the idea of the neutrino, but the particle would not be discovered until the 1950s. *Nature* famously rejected Fermi's paper, claiming that it was "too remote from reality."

From there, the discovery of new subatomic particles became progressively more worrying and complex. In 1934, Hideki Yukawa predicted mesons as the carrier of the strong nuclear force that binds atomic nuclei together, specifically protons and neutrons. Without this force, protons within the nucleus would repulse each other and fly apart. There was a great deal of confusion regarding what Yukawa's meson actually was. In 1936, Anderson discovered the muon through his cosmic rays, again using a cloud chamber. The muon bent less sharply than electrons under the same electromagnetic field, indicating a larger mass. It was thought to be Yukawa's meson due to its mass, and was called the mu-meson at first. However, it was soon shown that the muon did not interact with the strong force and as such could not be Yukawa's meson. As it turns out, the muon is similar to an electron but with a heavier mass. At the time, once the muon was shown to be different from Yukawa's meson, the muon did not fit with the existing framework of particle physics, famously prompting Isidor Isaac Rabi to ask, "Who ordered *that*?"

The actual Yukawa's meson, now known as the pion, would not be discovered until 1947, by Cecil Powell. Powell was investigating photographic emulsions of cosmic rays in the Andes mountains, and found "double mesons," in which a meson would decay into another similar meson. The tracks actually showed the pion, which would decay into the muon, which was still confused for a meson. Unlike the muon, the pion was shown to interact with the nuclear force and as such be the correct Yukawa's meson. Rabi's sentiments about the ever-growing particle zoo remained.

Around the time of the discovery of the true pion, the kaon was discovered. George Rochestor and Clifford Butler found unusual tracks in their cloud chamber in 1947, which indicated a particle of about the same size as the meson. However, this new particle had certain unusual properties and was labeled "strange," thus becoming the first strange particle to be discovered. Specifically, the kaon arose from strong interactions and had a slow decay, with a lifetime of about 10^{-8} to 10^{-9} seconds; ever since, strangeness describes the decay of particles in strong interactions.

Development of the Standard Model

The discovery of subatomic particles continued, without any order, further filling the particle zoo. Cosmic rays remained useful for particle discovery, as antiprotons and neutrinos were discovered for the first time in the middle of the 1950s using cloud chambers. However, particle accelerators were being developed simultaneously and gave rise to novel particles as well, including the antineutron. Theorists began to work on unifying the interactions of subatomic particles into a coherent theory. In 1957, Julian Schwinger suggested that perhaps the weak interaction and electromagnetism were connected in an "electroweak" theory. His graduate student, Sheldon Glashow continued studying this, and in 1961 added a "neutral current" to Schwinger's work that turned into the Z boson. Glashow's proposed set of symmetries would become the basis of the Standard model.

In 1964 Murray Gell-Mann postulated that many of the subatomic particles were made of "quarks". All hadrons are made of quarks and antiquarks. The interactions between quarks are mediated by the strong force, which is carried by gluons. Gell-Mann in his "Eightfold way" proposed only the up, down, and strange quarks. Gell-Mann's work was an alternative to Yukawa's meson, and worked better at short distances/high energies.

In 1964, Peter Higgs and Francois Englert proposed the existence of the Higgs boson. Their work was based on the prior work of Philip Anderson, who observed a similar interaction in the BCS theory of superconductivity and proposed, without working out the equations, that a similar mechanism could account for the mass of the W and Z bosons.

Three years later, in 1967, Steven Weinberg and Abdus Salam independently combined the Higgs mechanism with Glashow's earlier work, in a Standard Model that did not include quarks. Since then, the same model, along with the theory of quarks, has explained all of the results of particle experiments through the present.

Since 1967, experiments have for the most part served to validate the Standard Model. In 1968, using a technique called "Deep Elastic Scattering", which is a high energy extension of Rutherford scattering, physicists at the Stanford Linear Accelerator Center (SLAC) showed that the proton and neutron were made of constituent particles, further validating Gell-Mann's work.

At this time the Standard Model was still divided between electroweak interactions and strong interactions. But in 1970 Glashow, along with John Iliopoulos and Luciano Maiata, proposed the existence of a fourth quark, called a charm quark. In 1973 the number of quarks grew to six, when Makoto Kobayashi and Toshihide Maskawa showed that certain symmetries would only hold with 6 quarks. Almost immediately after the publication of this work, the charm quark was discovered at SLAC. Three years later, the bottom quark was discovered by Leon Lederman at Fermilab. By this point almost all physicists accepted the validity of the quark model. Also in 1973, the Gargamelle bubble chamber at CERN observed the neutral current added by Glashow, providing indirect evidence for the existence of the W and Z bosons.

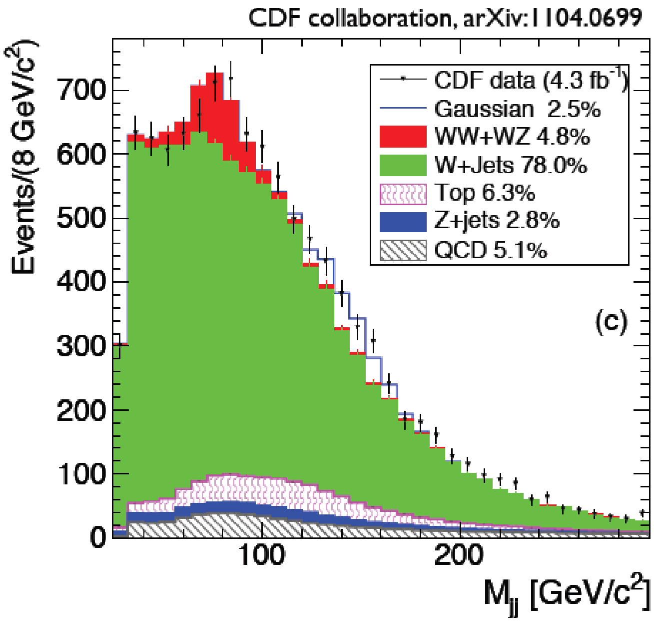
The discovery of the charm quark lead to the integration of quarks with the Weinberg's electroweak model, in what was the first modern incarnation of the Standard Model. It was known that hadrons had electroweak interactions, because of neutron decay, but the Standard model had not explained these interactions. With the introduction of the charm, top and bottom quarks, the Standard Model could finally predict almost all of the observed interactions.

At roughly the same time as these developments, Ray Davis and John Bahcall began work on the "Homestake" experiment. The neutrinos predicted by Fermi were included in the Standard Model, and by measuring the number of neutrinos passing through the Earth, Davis and Bahcall hoped to prove that stars were using nuclear fusion to generate their energy. However, their experiment yielded only ⅓ of the expected neutrinos. Their results were confirmed by Japanese experiments at KamioKande in the mid-1980s.

Nevertheless, this was a minor problem with a seemingly complete theory that seemed destined for complete verification. In 1979, gluons were observed for the first time. Four years later, in 1983, direct evidence for the W and Z bosons was found at the Super Proton Synchrotron. The only undiscovered particles were the top quark and the Higgs boson.

Particle detectors and the Standard Model

Each high energy proton-proton collision in the LHC generates hundreds of particles of widely varying type and momenta. To use experimental data to verify or challenge theoretical models, researchers must be able to calculate the likelihood of the observed results being seen under the assumption that a certain physics theories hold. Then, if the experimental results deviate significantly from the predictions provided by the assumed theories, the hypothesis can be rejected and the opposite of the assumed theory must be true. In order to establish the existence of a Higgs-like particle, researchers assumed that no particle exists within the mass range of the theorized boson with the certain properties of the boson. They then compared the rate at which certain processes occurred experimentally within the LHC to the theorized rates assuming no Higgs-like boson exists. Finding these rates to differ significantly (by more than 10 standard deviations as of March, 2013), researchers rejected the hypothesis that no Higgs-like boson exists.



The figure above shows the production of a W boson and two parton jets with the interesting physics showing up as only a small deviation from the theoretically predicted background of the null hypothesis. Clearly, an accurate prediction of the background is critical to verifying physics such as the Higgs boson. In order to predict this background, we look at a given process and identify the subprocesses that contribute to it.

This methodology requires particle physicists to be able to do two tasks: reconstruct the events that occurred within the LHC from calorimetry and sensor data collected by the detectors, and compute the probability of an event occurring given certain modifications to the Standard Model. Both of these tasks are highly non-trivial and require the use of sophisticated and time-consuming computational methods necessitating the use of CERN's Worldwide Computing Grid for computing power.

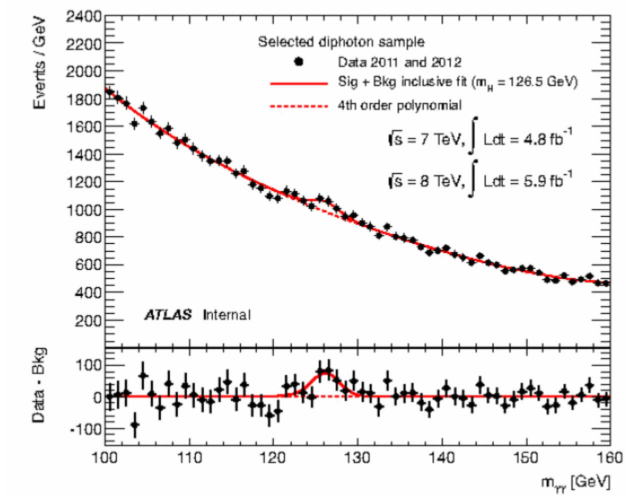
To compute the probability of a specific event like $H \rightarrow 4e$ occurring, physicists would like to calculate *matrix elements*, which denote the probability amplitude of a certain scattering process resulting in particles with specific momenta. By integrating over all possible momenta for the resulting particles, the phase space, physicists would be able to find the probability that the generic process occurs. Unfortunately, matrix elements cannot be determined exactly except in the simplest cases. Instead, physicists resort to Feynman diagrams and experimentally suggested models, which approximate the matrix elements.

Modern Developments

Top Quark and Higgs Boson

Despite the almost-continuous progress made during the previous decades, particle physics went into something of a lull after the mid-1980s. The requisite energies for observing the missing particles were too high for existing colliders. Fermilab completed the Tevatron in 1986, and despite the expected discovery of the top quark, nothing appeared. The Tevatron was named as it was the first collider to reach energy levels above 1 teraelectronvolt (TeV). The D0 experiment was added to the Tevatron specifically to aid in the discovery of the top quark. It was completed in 1993, and in 1995 the top quark was discovered. This was the last undiscovered quark, nearly completing the standard model.

The Large Hadron Collider (LHC) was built at CERN with the purpose of locating the Higgs Boson in mind, using the 27 km loop that had previously housed the Large Electron Positron (LEP) Collider. The LHC is notable for using superfluid helium to create superconducting magnets, allowing for energies up to 7 TeV. The first stable collisions began in April 2012, and in July 2012, the Compact Muon Solenoid (CMS) and A Toroidal LHC ApparatuS (ATLAS) detectors jointly announced that they had discovered a particle consistent with the expected properties of the Higgs boson. These findings have since been refined so that most scientists are confident in the existence of the Higgs. The graph below illustrates the deviations in decay patterns that led to the discovery of the Higgs.



We are now at a crossroads in particle physics. All the parts of the Standard Model are completely verified, but the majority of matter in the universe, so-called dark matter and dark energy, is still unexplained. Neutrinos were used to prove that stars use nuclear fusion to generate energy, and extensions of the Standard Model may help elucidate some of the universe's mysteries. The LHC is undergoing renovations until April/May 2015 to increase the energy of collisions, and explore physics beyond the Standard Model.

Neutrinos

Nearly all experiments involving neutrinos occur on extremely large scales, in large part due to difficulty in detecting even a single neutrino event. Davis's Homestake experiment used 100,000 gallons of perchloroethylene (dry cleaning fluid) to detect neutrinos. In 1996, the Super-Kamiokande observatory was completed in Japan, to study solar neutrinos. The Super-Kamiokande Neutrino Detection Experiment (Super-K) resides nearly 1 km underground, beneath Japan's Mozumi mine, and is comprised of a tank filled with pure water, over 30m in length and height. The tank contains inner detectors (photomultipliers incorporated as part of the inner structure) and outer detectors. In 1998, it announced the first evidence of neutrino oscillation.

Neutrino oscillation also gave credibility to Davis's earlier results. There were three flavors of neutrinos, and Davis could only find ⅓ of the expected neutrinos, because he could only detect one of the 3 types of neutrino. The other ⅔ were oscillating in the muon and tau flavors. However, the Standard Model through 1998 predicted massless neutrinos, neutrino oscillation implied that neutrinos actually had mass. This has not yet been resolved, but there are currently a number of different potential solutions which do not require a new standard model. In the proposed "seesaw mechanism", there would be "right-handed" neutrinos with high mass.

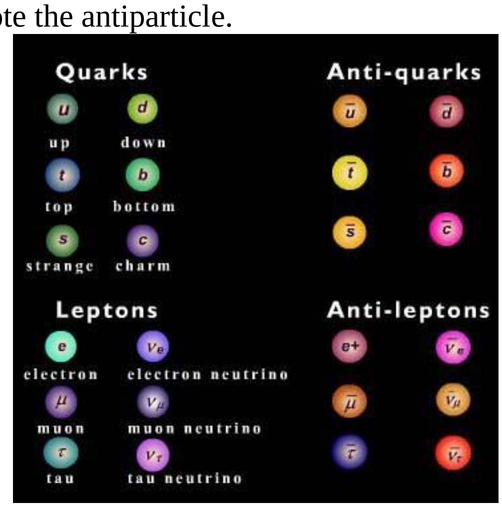
These occur in supersymmetry, which is explained in more detail later in this paper. These right-handed neutrinos are potential dark-matter candidates.

The Ice Cube South Pole Neutrino Observatory, which comprises a cubic kilometer of ice near the South pole, detects incident neutrinos from the hundreds of digital optical modules (DOMs), which make use of photomultiplier tubes, buried beneath the surface and extending from depths of nearly 1500 m. The detectors, which reside at the surface of the observatory, register hundreds of neutrinos from below (i.e., which pass through the surface of the Earth in the Northern hemisphere and continue through the Earth until they reach the South Pole detector) each day. Until recently, it was not known whether neutrinos were massless particles. However, the neutrino could only oscillate between distinct flavors if they indeed had a nonzero mass. In the end, data from DeepCore subdectector of IceCube have shown evidence of neutrino oscillation. Other notable results include detection of around 30 extrasolar neutrinos by the Antarctic Muon And Neutrino Detector Array (AMANDA), in addition to a pair of high-energy neutrinos in 2011.

Neutrinos have recently been in the news due to some unexpected experimental results at the LHC. Neutrinos produced from the proton-proton collisions frequently occurring in the operations of the LHC can travel through the Earth to the Gran Sasso National Laboratory in Italy, a distance of roughly 730 km. Despite the vast amounts of energy generated by proton-proton collisions in the LHC, muon neutrinos are the heaviest type of neutrino that should be generated. However, at Gran Sasso, tau neutrinos have been detected in a statistically significant quantity, providing further evidence that neutrinos oscillate between flavors potentially by way of the weak force. Results from one test in December 2011 indicated that these neutrinos may have traveled faster than the speed of light. However, further analysis revealed that a poorly tuned clock, and a fiber optic attachment misalignment accounted for the difference. Nonetheless, the elusiveness of the neutrino and the difficulties in studying it puts it at the forefront of current research in physics. It remains one of the few unexplained portions of the standard model.

Antimatter

The modern theory of antimatter was first introduced by Paul Dirac in a 1928 paper. Dirac discovered by the relativistic version of the Schrodinger wave equation for electrons predicted for the possibility of antielectrons. In 1932, Carl Anderson then discovered the existence of these particles, and termed them positrons. In modern notation, if a is used to denote a particle, then $\bar{a}$ would denote the antiparticle.



Antimatter is composed of antiparticles, which have the same mass, but opposite charge, and lepton and baryon numbers compared to their “normal” matter counterparts (i.e. they have the exact opposite quantum numbers). Particle-antiparticle interactions lead to annihilation of both entities. Any set of particles may be produced from the collision as long as their total quantum numbers are zero and energy and momentum are conserved. The energy from the collision is usually converted into a force carrier particle, such as a gluon, W/Z boson, or a photon. Low energy annihilation tend to favor photons, as they are massless, while high energy annihilations produce a wide variety of heavy particles. The release of energy is available to do work, proportional to the total matter/antimatter mass with $E = mc^2$.

Future Developments

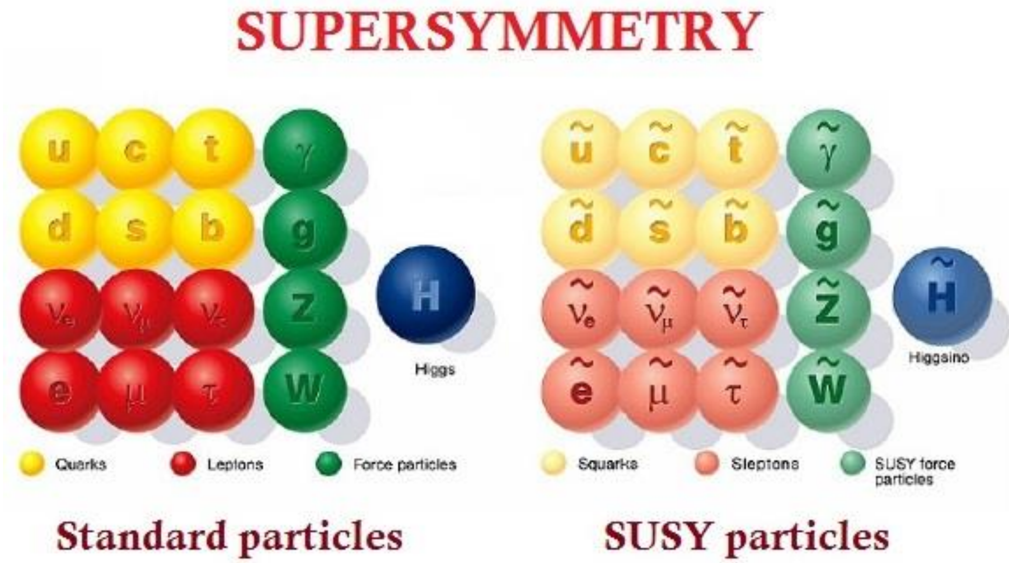
Grand Unified Theories

The Standard Model is the most fundamental verified model of the universe, but physicists are continually looking to simplify, and explain more with less. The Standard Model is an effective field theory, as the strengths of the interactions depend on the energy scale. It is known that at higher energy scales, the strengths of the strong, electromagnetic, and weak interactions become closer. Grand unified theories examine the possibility that the three interactions are all lower-energy manifestations of a single, unified interaction. The energy scales at which unification would occur are several orders of magnitude beyond current accelerators, but there are more indirect ways of testing such theories. The unified interaction conserves neither baryon nor lepton number but instead their difference, and so such theories predict that the proton should decay into a positron (and mesons, to conserve momentum). The high energy required for the interaction makes this extremely rare; current predictions are of a half-life on the order of 10^{32} years. There has been no statistically significant indication that the proton can undergo such a decay, although detectors similar to neutrino detectors are currently searching for such evidence.

Supersymmetry

Supersymmetry gained traction in the 1980s as a way to avoid “fine tuning” of the parameters of grand unified theories. The central idea of supersymmetry is that there is a correspondence between bosons, with integer spin, and fermions, with half-integer spin. All quarks and leptons have supersymmetric, bosonic partners known as “squarks” and “sleptons”, while the gauge bosons have fermionic partners known as the “photino”, “wino”, “zino”, “gluino”, and “Higgsino.” The masses of these supersymmetric partners is thought to be on the order of a few TeV, which is just at the current limits of detection. Due to a selection rule in supersymmetry, such partners are only created in pairs; this means that a single supersymmetric particle is unable to decay to Standard Model particles. The lightest supersymmetric partner is therefore stable, and is a dark matter candidate (the right-handed neutrino, or “neutralino”).

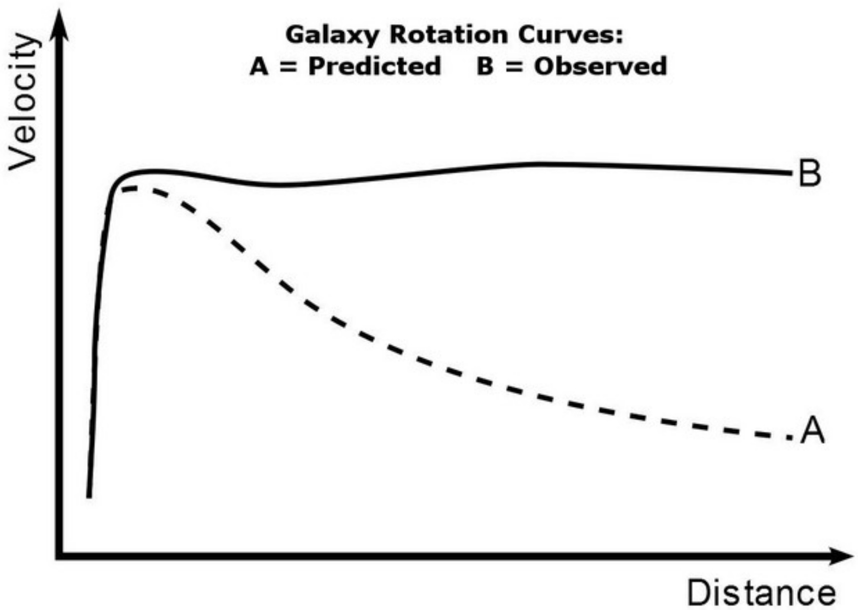
However, while supersymmetry generally predicts a single partner for each Standard Model particle, various supersymmetric models predict multiple partners for the Higgs boson. The Minimal Supersymmetric Standard Model (MSSM) in particular predicts five total variants of the Higgs boson, while the Near-Minimal version (NMSSM) predicts the existence of two. According to the MSSM, two of the Higgs variants would be CP-even, differing only in mass, one would be CP-odd, differing in charge or parity, and two would have yet another distinct mass while being oppositely charged. An experimental divergence released in late 2012 determined masses of both 123.5 and 126.6 GeV for the Higgs particle and has consequently been suggested as evidence of supersymmetry, however the result in question has not been duplicated and mechanical errors have not been ruled out. Further experiments at higher energy levels at the LHC are planned in order to uncover the other possible states of the Higgs if they exist, once the LHC facility is upgraded to permit energy levels of up to 14 TeV.



In recent years, however, supersymmetry has suffered setbacks. One blow to it came with more precise measurements of the electron's electric dipole moment. The electric dipole moment represents the way in which the observed electric field deviates from that of a point charge. While the Standard Model predicts extremely small maximum values for the electric dipole moment of the electron and neutron, supersymmetric mechanisms are able to give values that are not quite as small and are currently being tested. Negative results have already put restrictions on some of the parameters of supersymmetry. Another blow came with the decay of the strange bottom meson B_s. This neutral meson may transmute to its antimeson, but its large mass suggests that its decay should involve supersymmetric mechanisms. As per observations at LHCb in 2012, however, the probability of decaying in a certain way is lower than predicted in most supersymmetric models; to explain the data, such models would need to tune their parameters in a way which begins to remove the original inspiration for the theory. Despite this, supersymmetry has not been rejected entirely, and there remain several supersymmetric models for particle physics.

Dark matter and candidate particles

In 1933, Fritz Zwicky observed a difference between the amount of mass in the Coma Cluster of galaxies as measured by brightness (visibility) and the amount of mass as measured by velocity. The second estimated mass was almost four hundred times larger than the visible mass. This is known as the Missing Mass Problem.



The Missing Mass Problem in galaxies (also noted as the flattening of the rotation curves at large radii for disc galaxies, or the mass discrepancy), is typically resolved through the introduction of a type of matter called dark matter (DM), named for its lack of interaction with the electromagnetic force. Although exact figures vary, dark matter is theorized to comprise around 23% of all matter in the universe; directly observable, ordinary matter is thought to comprise only 4%. While the exact composition of DM is still unknown, possible candidates include supersymmetric particles, as mentioned above. Such matter might be produced in collisions at the LHC or other particle colliders, but would pass through detectors unnoticed. In this way, any "missing" transverse energy or momentum at the end of these collisions could be due to the creation of DM.

In addition to neutralinos, several other hypothetical particles have been suggested as dark matter candidates, including axions, strangelets, and weakly interacting massive particles (WIMPs). Axions are predicted to be chargeless and have a maximum mass of 1 eV, hence, models that include axions substitute them for neutralinos as a dark matter candidate on the grounds that the axion would be the lightest supersymmetric particle. Recent astrophysical measurements have revealed a consistent 10% increase in relative x-ray intensity where the Earth's magnetic field faces towards the Sun, a result that could be explained by solar-produced axions emitting x-rays upon impacting the Earth's magnetic field.

Strangelets arise from Edward Witten's "strange matter hypothesis," which postulates that for a large collection of quarks, the configuration that contains roughly equal numbers of up, down, and strange quarks would be stable, even though baryons that contain strange quarks, such as the Λ^0 (uds), decay to products that only contain up and down quarks. No strangelet has ever been detected, though they are a focus of two current major projects - the Alpha Magnetic Spectrometer (AMS) at CERN, and the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory in New York. (Strangelet theory has also spawned a notable doomsday scenario - large strangelets may be more stable than small strangelets, in which case a single strangelet might transmute any ordinary matter that it contacts, creating successively larger stranglets until the Earth is annihilated into strange matter.)

Finally, WIMPs are yet another type of particle related to supersymmetry, and interact only through gravity and the weak force, hence their name. WIMPs are one of the most intriguing dark matter candidates because, by definition, the cross section governing their interactions cannot exceed the cross section that arises solely from the weak force. This condition is thought to match the density of dark matter prevalence in the universe, since the magnitude of the cross section should be inversely related to the amount of dark matter that endured after the end of annihilation between the dark matter particle and its anti-particle.

Dark energy

Often thought of as the fifth force, dark energy (DE) is the energy theorized to comprise the remaining 70% of the universe (based on an equivalence drawn between mass and energy). DE would explain the repulsion amongst matter, and therefore the expansion of space in between matter in the universe. DE can actually be either attractive or repulsive, but became repulsive ten billion years ago, creating what is now the inflationary period of the universe. Two main theories of the behavior of DE currently exist: those of quintessence and the cosmological constant. Future plans at the LHC endeavor to probe into such theories as supersymmetry and string theory, which could lend evidence to one of these theories over the other and give further insight into the fate of the universe.

Mass Production of Antimatter

To form antimatter, antiparticles bind with each other. This is analogous to particles forming matter. For example, An antiproton and a positron can combine to form antihydrogen. Though theoretically complex, antimatter is possible, but no antiatoms more complex than antihelium have ever been observed or produced. Some antiparticles and antiatoms that have been produced include the antiproton in 1955 at the University of California, Berkeley (which won the 1959 Nobel Prize in Physics), antineutron in 1956 at the Lawrence Berkeley National Lab, antideuterium in 1965 at CERN, antihydrogen in 1995 at CERN, and positrons in 2008 at the Lawrence Livermore National Laboratory where a laser drove electrons through a 1mm radius gold target's nucleus.

The production of antihydrogen at CERN in 1995 was landmark event. Specifically, 9 antihydrogen atoms were produced implementing SLAC/Fermilab concept during the PS210 experiment. However, these particles were very "hot" or energetic. This experiment was performed using the Low Energy Antiproton Ring (LEAR) at CERN. In 2005, the ALPHA Collaboration was formed, with a goal to create "cold" or less energetic antihydrogen, which are easier and much better suited to study. Progress was made in 1999, when CERN activated the Antiproton Decelerator, which helped slow antiprotons from 3.5 GeV to 5.3 MeV, which is still too hot for studies.

In 2002, ATHENA produced the first "cold" antihydrogen by decelerating antiprotons through the Antiproton Decelerator, passing them through a thin sheet of foil, and then finally capturing them in a Penning-Malmberg trap. However, this process if very inefficient, with only 0.1% of them make it to the Penning-Malmberg trap. The antiprotons are still hot when initially trapped. Thus, to cool them further, they are mixed into an electron plasma; the electron plasma will cool via cyclotron radiation, which sympathetically cools antiprotons via Coulomb collisions. The electrons are then removed by short-duration electric fields, which leaves antiprotons with energies less than 100 meV.

Concurrently, a small cloud of positrons is captured from radioactive sodium in a Surko-style positron accumulator. The cloud is then recaptured at a second trap near the antiprotons. Trap electrodes then tip the antiprotons into the positron plasma, where some combine with antiprotons to form antihydrogen. These antihydrogen antiatoms quickly hit trap walls and annihilate, existing for a couple of microseconds.

After successfully producing "cold antihydrogen," the secondary problem of trapping/holding the antiatoms for a long enough time to study arises. One possible option is to trap using the magnetic minimum (minimum-B) trap by taking advantage of the magnetic moment of antihydrogen antiatoms. ALPHA Collaboration has trapped 38 antihydrogen antiatoms for ⅙ second in their first time antimatter trapping in November 2010. Another trap was achieved on April 26, 2011 when ALPHA trapped 309 antihydrogen atoms for 1000 seconds (~17 minutes), the longest ever trap. This helped spark research into the spectral properties of antihydrogen.

Another limiting factor would be the availability of antiprotons. CERN, when fully operational, produces 10 million antiprotons/min. Even assuming a 100% conversion of antiproton to antihydrogen, it would take 100 billion years to make 1 mole of antihydrogen. Hence, investigating more efficient antiproton generation and antihydrogen cooling techniques remains at the forefront of modern physics.

Baryon Asymmetry

Baryon asymmetry refers to the fact that there is an imbalance between baryonic matter and antibaryonic matter in the observable universe. In other words, much of the observable universe is composed of ordinary matter, as opposed to a more symmetric combination of matter and antimatter. The process by which this asymmetry arose is termed baryogenesis. Neither the standard model nor the theory of general relativity provides an adequate explanation for this, so it is a natural assumption that universe should be neutral with all charges conserved; the Big Bang should have produced equal amounts of matter and antimatter. Consequently, equal amounts of matter and antimatter should exist today, assuming perfect symmetry between the two classes of particles.

However, quite clearly, almost all of the universe around us is formed from matter as opposed to antimatter. Since a large fraction of the original matter and antimatter was annihilated in the early Universe, the asymmetry between matter and antimatter most likely sprang up as the temperature of the Universe dropped. Antimatter today is only generated from high energy interactions mediated by the weak force that need to conserve charge and mass. Since the particles involved in such interactions carry such great momentum, it is very rare for antiparticles to come into close enough contact at low enough energies to bind together. In fact, the antihelium nucleus is the largest antinucleus to have ever been observed to date. Additionally, it is suspected that the first unionized antihydrogen to have ever existed in the Universe was created by CERN in the LEAR experiment.

Although there is no one consensus to explain the phenomenon, most explanations involve modifying the standard model of particle physics. The modification, usually involving the weak nuclear force, would allow some reactions to proceed more easily than their opposite. This is called "violating CP symmetry" in weak interactions (CP stands for Charge conjugation Parity). This violation would allow matter to be produced more commonly than antimatter in the conditions immediately after the Big Bang. The LHCb experiment is dedicated to studying CP violation processes in decay of B mesons; the LHC is a good source of BA variety of b-hadrons, such as Bu, Bd, Bs, Bc and b-baryons, producing them at high rate. Even though the LHCb, BaBar, and Belle experiments have so far identified small deviations between the production of matter and antimatter, its results are insufficient to explain the huge incongruency between matter and antimatter in the observable Universe.

Penta/tetraquark theories

It is currently understood that no quark can exist in isolation. Presently, the hadrons (i.e.

quark matter) include two groups: baryons and mesons. However, it has previously been theorized that a so-called exotic baryon, comprised of more than three quarks or additional particles, exists. One recently popularized notion is that of the pentaquark, which was thought to take on any of a number of possible compositions: the so-called Θ^+, with two up, two down and one anti-strange quark; the Φ^{--}, two down, two strange, and one anti-up quark; the Θ_c^0, with two up, two down and an anti-strange quark. Of these, experiments have only ever given evidence of the Θ^+ pentaquark. In 2003, the Laser Electron Photon Experiment at Spring-8 (LEPS) reported evidence for pentaquarks of mass 1540 GeV/c^2, and subsequent experiments by numerous other sources confirmed similar results. LEPS continued testing this theory for several years through backward Compton scattering. Despite this, the 2008 *Review of Particle Physics* ruled out the possibility of existence of the Θ^+, stating that these results had all been due to experimental error, despite overall certainties above 4 sigmas. There is a further possibility that would give evidence to the pentaquark theory, specifically the decay of a gamma-ray deuterium interaction resulting in one kaon, one anti-kaon, a proton, and a neutron. This controversy continues, as experimental results with over 5 sigma (the accepted limit for particle physics) continue to be published.

In addition to pentaquarks, tetraquarks, consisting of four quarks, have also been proposed. One of the major difficulties of detection is distinguishing between a tetraquark and two mesons. A possible tetraquark particle would be the first known exotic meson if confirmed. Data from the 2003 Belle Experiment (study of CP violation) in electron-positron collisions, revealed the possibility of a particle referred to as X(3872). Other possibilities of tetraquarks include Fermilab's SELEX's 2004 $D_{sJ}(2632)$ state and 2009 Y(4140) state, Belle's 2007 Z(4430) and Y(4660) states, and LHCb's confirmation of the Z(3340) with significance of over 13.9 σ. In addition to this, in 2010, scientists from Quaid-i-Azam University and DESY announced that there exists a well-defined tetraquark resonance in connection with the Upsilon meson.

The existence of exotic mesons and baryons have broad implications for astrophysics in the future. Looking at the traditional model of a neutron star that states it is made out of neutrons, which consist of 2 down quarks and 1 up quark, it was originally thought that all particle interactions inside neutron stars would be between neutrons. However, if tetraquarks were to exist, it would be possible that particle-particle interactions inside neutron stars would be strong enough to create tetraquarks. Furthermore, this could even lead to the production of pentaquarks and hexaquarks, or even that quarks could interact individually without being bound into color neutral particles. This would introduce the notion of a hypothetical object known as a quark star. As the scientists continue to look for the existence of tetraquarks, pentaquarks, etc., further confirmation of their existence will not only change the way we look at particle physics and QCD, but also force us to reexamine our assumptions about the interior of neutron stars.

Conclusion

The Standard Model is one of the great theories of physics. Conceived in the mid-1960s, experiments in the last 50 years have almost universally provided more evidence for the correctness of the model. Less than two years ago, the Standard Model was "completed" with the discovery of the Higgs boson at the LHC. However, the struggle to discover and fully explain the behavior of all matter in the universe is ongoing. 96% of the universe's matter remains unexplained. As the technological improvements and upgrades made at CERN and other research institutions provide higher quality data, our understanding of the Standard Model and its possible extensions is advanced.

Glossary

Baryon - A particle made of three quarks, such as a proton or neutron.
Boson - A force-carrying particle in the Standard Model; more generally any particle with integer spin.
CP Violation - In CP symmetry, if a particle is exchanged with its antiparticle, then the laws of physics should remain the same. CP Violation breaks this symmetry, and could potentially help explain the matter-antimatter asymmetry in our observed universe.
Fermion - A particle with half-integer spin; particles of matter tend to be fermions.
Hadron - A particle that interacts via the strong interaction; all hadrons are presumed to be made of quarks and antiquarks.
Higgs Boson - A feature of the Higgs field, which is responsible for giving mass to the Standard Model particles.
Lepton - A half-spin particle that does not interact with the strong force, and is subject to the Pauli exclusion principle.
Meson - A quark-antiquark pair.
Pion - A meson consisting of only up, down, anti-up, and anti-down quarks.
Spin - A particle's intrinsic angular momentum. This is purely a quantum phenomenon, there is no classical spin.

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