God Particles: The Constituents of Particle Physics and the Revolutionary Standard Model

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Billions of years ago, the cosmos was but a speck with infinite density and temperature. However, after exceeding the threshold of Planck's time, the four fundamental forces emerged, and matter—and its counterpart, antimatter—was born. A few nanoseconds later, the once small, gilded speck of existence began to rapidly and violently expand outwards in a ferocious burst of colossal energy. The universe cooled off and expanded exponentially, the fundamental particles of existence formed, and eventually said particles coalesced to form protons. Electrons and protons, subsequently, collided to form deuterons (the nucleus of a deuterium atom)[1], deuterons collided to form helium and trace amounts of lithium, and, a couple hundred thousand years later, stars formed, hydrogen was created, and an "elemental" cascade of sorts kicked off to form all the various elements that dot the periodic table today (with the obvious exception of the man-made elements). It was in those first few nanoseconds, however, that the more complex, or unusual particles that now populate the Standard Model of particle physics arose.

CERN states that "everything in the universe is found to be made from a few basic building blocks called fundamental particles, governed by four fundamental forces. Our best understanding of how these particles and three of the forces are related to each other is encapsulated in the Standard Model of particle physics"[2]. We already understand atoms. They are the smallest possible

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representation of an individual element and can bond to form molecules and complex compounds. Yet atoms are not the smallest piece of matter in the universe; they are composed of the quite well-known proton and neutron that form the nucleus, as well as the electron. However, even these particles can be broken down into smaller, elementary particles: the smallest building blocks of the universe.

1 An Important Differentiation

The elementary particles are classified into two discrete categories: bosons and fermions, and there is a very simple but extremely important difference between the two. A boson is any particle that has a whole integer spin (e.g 0, 1, 2, etc), whereas a fermion, such as the electron, is any particle that has a half-integer spin (e.g. $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, etc). What exactly is spin? Physics professor Victor J. Stenger at the University of Hawaii defines it as "the total angular momentum, or intrinsic angular momentum, of a body. The spins of elementary particles are analogous to the spins of macroscopic bodies. In fact, the spin of a planet is the sum of the spins and the orbital angular momenta of all its elementary particles. So are the spins of other composite objects such as atoms, atomic nuclei, and protons"[3]. The importance of spin and the reason why physicists have separated particles into bosons and fermions is best seen on a grander scale. The first consequence of varying spins, is that every fermion has its own respective antiparticle: a particle that carries the exact opposite charge as its counterpart. The electron, for example, is negative, while the electron's antiparticle, the positron, is positive. In general, bosons are their own antiparticle and some bosons are also the antiparticles of other bosons

The second and more important difference is the Pauli Exclusion Principle, which states that "no two fermions can occupy the same quantum state"[4]. In other words, no more than two electrons may occupy the same orbital in an atom and the two that do must have opposite spins. Suppose we have an atomic nucleus, composed of three protons and three neutrons. If we were to add an electron, and then another one, nothing major would happen aside from the fact that the first orbital or the "ground state" would fill up. However, if we were to add a third electron, it would have to move to a new energy level as the first orbital is already filled up. It is because of this simple principle that the periodic table exists the way it does, and why each element has its own unique properties:

because every element has a unique electron configuration. Bosons, however, simply do not abide by this rule, and they can occupy the same quantum state, meaning that they are able to carry force–a property largely responsible for the existence of the Standard Model. Due to their ability to aggregate, bosons with the same energy such as the photon can carry and transmit forces. There is no real satisfying explanation for why exactly bosons violate the PEC and are able to carry force as a result of it [5].

On a side note, since bosons are particles that do not obey the PEC, they are not governed by Fermi-Dirac statistics[1][6] and thus fall under Bose-Einsten Statistics[7]. This gives rise to exotic states of matter such as the Bose-Einstein condensate and superfluid. Essentially, bosons, at low temperatures, are able to condense tightly into the same quantum state and form Bose-Einstein condensate[8]. A superfluid, most commonly observed as liquid helium cooled to near absolute zero, is a state of matter in which a liquid loses almost no kinetic energy and experiences zero friction[9]. Both of these states of matter are only possible because bosons obey Bose-Einstein statistics.

2 The Standard Model

The Standard Model is a tool that helps physicists organize and properly orient the purpose of each elementary particle and their relation to one another. It is separated into four discrete categories: the leptons, the quarks, the gauge bosons, and the scalar bosons. It can be analogized to the Periodic Table of Elements, as it provides a handy overview of all primary components of a specific field of study. The Periodic Table, utilized by chemists and biologists alike, is grouped into various rows and periods in which elements possessing the same physical properties can be found. The Standard Model is also separated and organized by properties, as particles that share the same features are grouped into one category [2]. Moreover, there are deeper levels of organization in the Periodic Table. An element can either be a metal, metalloid, or nonmetal. This compartmentalization is also present in the Standard Model in the form of the four aforementioned categories of particles.

It is important to note that the Standard Model does not only logically organize the fundamental particles. Rather, it also illustrates how these particles

[1] Quantum statistics set that governs fermions.
[2] e.g. Gauge bosons all have a similar function and 1 integer spin

interact with each other and how the four fundamental forces [3] govern these particles. Thus, the Standard Model can be separated into two major categories: the matter particles, responsible for the existence of everything, and the force particles, responsible for the forces that control everything.

3 Quarks: The Fundamental Constituents of Matter

The matter particles are the building blocks of the universe, and they compose all of the matter in the universe[4]. Phys.org states that the "Standard Model of Particle Physics, which is strongly supported by extensive experimental results, suggests the material universe is assumed to be built by a small number of fundamental particles: quarks and electron-like particles called leptons"[10].

There are six flavors, or types, of quarks: up, down, top, bottom, and the peculiarly named charm and strange. All six flavors of quarks come in a wide range of masses, yet only up and down quarks are stable and naturally occurring[5]. Quarks bind to form hadrons, or any particle made up of quarks. There are two types of hadrons: the baryon[6], composed of three quarks, and the mesons, composed of one regular quark and one antiquark. Therefore, there are technically 12 quarks, and six of them are antiquarks: the antiup, antidown, antistrange, anticharm, antitop, and antibottom[11].

Individual quarks have charge, and since they are the components of hadrons, they determine the hadron's charge as their lack of internal structure means that they cannot be decomposed into smaller particles. In other words, a quark is the most minuscule particle imaginable, and it can, unlike a nucleus, not be cut or splintered into various smaller components. Up, charm, and top quarks have a positive charge of $\frac{2}{3}$, whereas down, strange, and bottom quarks have a negative charge of $\frac{1}{3}$[11]. Since protons are composed of one down quark and two up quarks, and neutrons are composed of two down quarks and an up quark, we can use simple arithmetic to understand the origins of a hadron's charge. $\frac{2}{3} + \frac{2}{3} - \frac{1}{3}$ is equal to 1, and a proton has a charge of +1. $\frac{2}{3} - \frac{1}{3} - \frac{1}{3}$ is equal to 0, and a neutron has a charge of 0.

The positive charge of protons is what attracts electrons, and electrons are

[3] Gravity, electromagnetism, strong nuclear, and weak nuclear forces.
[4] All of these matter particles are fermions.
[5] The rest are produced in laboratory environments.
[6] e.g. Protons and neutrons.

ultimately responsible for bonding between the elements. Thus, we begin to understand the importance of quarks and their properties. Up and down quarks, combined with the electron, essentially compose all known matter in the universe.

4 Leptons: The Electron Family

Particles are considered leptons if they do not interact with the strong nuclear force but do interact with the weak nuclear, electromagnetic, and gravitational forces. The lepton class comprises the electron, tau, and muon. The tau and muon are simply heavier siblings to the electron and, like the electron, carry an electrical charge. Both are rare and almost undetectable due to their short lifespan[10]. Britannica states that "a muon is relatively unstable, with a lifetime of only 2.2 microseconds before it decays by the weak force into an electron and two kinds of neutrinos." The tau is even more unstable than the muon as it is "similar to the electron but 3,477 times heavier," and has "a mean life of 2.9×10^{-13} second, and it decays readily via the weak force into other particles"[12]. The tau is much, much heavier than both the muon and electron, and is thus "the only lepton massive enough to decay into hadrons, particularly into pions," the lightest type of meson[13].

Each lepton also has its own neutrino variant: the electron has the electron neutrino, the muon has the muon neutrino, and the tau has the tau neutrino. A neutrino is a variant of a lepton that has no electrical charge and has an extremely minuscule mass, similar to that of the electron. In addition to the electron[7], neutrinos are generated in large amounts by stars in nuclear decay reactions, and are some of the most abundant types of particles. In fact, they interact with and pass through our bodies about 100 trillion times every second[14]. They are also perhaps one of the most aptly named particles of the Standard Model, as they have an extremely minute amount of mass[8] and have a neutral charge.

An important remark that must be made is that the tau and muon are revolutionary particles because they prove the long-hypothesized notion of familial triplicity in the Standard Model. CERN states that "the existence of different families is one of the most important open questions in particle physics. The basic structure of matter, with the up and down quarks, (the electron and the

[7] And its antiparticle, the positron.

[8] So little, even, that neutrinos were long considered to have no mass at all.

electron neutrino) appears to have two heavier replicas with identical interactions: the charm and strange quarks with the muon and the muon neutrino; and the top and bottom quarks with the tau lepton and its neutrino"[15]. There is no plausible explanation for this triplicity (or quadruplicity if one considers the various neutrinos), yet it has been presumed that the heavier set of particles with the tau lepton likely has more sensitive interactions with the Higgs field that generates mass[15].

5 Gague Bosons: Carriers of Force

While matter particles can be thought of as the building blocks of the universe, force particles are the glue that holds them together. The matter particles are the bricks in a wall, and the force particles are the cement that holds it together.

There exist four fundamental forces in our universe: gravity, the invisible hand that ties the universe together and keeps the planets in orbit around the sun; the electromagnetic force, the interaction between charged objects that is responsible for light; the strong nuclear force, the force responsible for binding the quarks into hadrons and keeping the nucleus together; and the weak nuclear force, responsible for subatomic decay and the nuclear fusion that occurs in the sun. Each of these fundamental forces is governed by its own fundamental particle and said fundamental particles are each responsible for keeping the matter particles in place. There is one glaring exception to the aforementioned statement: gravity. A particle that corresponds to gravity has not yet been discovered, and is thus not represented on the Standard Model.

CERN affirms that "three of the fundamental forces result from the exchange of force-carrier particles, which belong to a broader group called 'bosons.' Particles of matter transfer discrete amounts of energy by exchanging bosons with each other"[16]. These bosons are the gluon, which carries the strong nuclear force, the W+, W-, and Z bosons, which carry the weak nuclear force, and the photon, which carries the electromagnetic force. Gluons act as the glue[9] that keeps quarks pushed into hadrons, and those protons and neutrons subsequently pressed into a nucleus[16].

Electrons orbiting the nucleus are attracted to it via the electromagnetic force, which is the attraction between opposite charges and the repulsion between like charges. As an electron absorbs energy, it jumps to an outer orbital

[9] i.e. As the strong nuclear force.

and releases energy in the form of photons, or light. Light consists of electric and magnetic fields circulating through empty space, meaning that photons are the carriers of the electromagnetic force. The electromagnetic force is the most commonly experienced force in the sense that it is responsible for you not falling through your chair right at this moment. The electrons in your body are repelling the electrons in your chair and preventing the atoms from passing right through each other[16].

Particles can sometimes transform into entirely different particles through a process known as particle decay, for which the weak force is responsible. The weak force acts on quarks[10] in order to change the identity of the entire particle. In other words, if a quark decays into another flavor of a quark, the encapsulating particle might change into an entirely different one through the weak nuclear force. The electron's heavier siblings, the muon and the tau, only exist under simulated laboratory conditions and decay very quickly into lighter particles. The weak nuclear force is responsible for this decay and it involves an exchange of force carrier particles: the W+, W-, and Z bosons[17].

It is best to look at a hypothetical situation to explain the weak nuclear force and its carriers. Suppose a neutron encountered a neutrino that has a W+ boson. The weak nuclear force would work as follows: the neutrino would transfer its W+ boson to the neutron, thus transforming the neutrino into an electron as it has lost a positively charged W boson. The W+ boson would encounter, for instance, one of two down quarks that comprise neutrons, and change it from a slightly negative quark to a slightly positive quark. The down quark would transform into an up quark, and the whole neutron would subsequently become a proton. The weak nuclear force is the reason why many radioactive elements, such as radium and polonium, exist. Without it, nuclear fusion in the sun's core would not exist, and life on earth, subsequently, would not exist.

6 Scalar Bosons: The Higgs Boson

All elementary particles, aside from the photon[11], have some mass (as insignificant as it may be). The question of where these particles got their mass from is a question that has long confounded physicists. Only until 2012, when a particle long thought to be the Higgs Boson was finally discovered at a CERN laboratory, was light shed on a conundrum that had sparked much debate among

[10]Or leptons, but typically quarks.
[11]The photon can travel at the speed of light as a result of its masslessness.

physicists[18]. In 1964, theoretical physicists Peter Higgs, Francois Englert, and Robert Brout proposed a theory to explain how particles get their mass[18]. They proposed that shortly after the Big Bang, a force field, called the Higgs Field, came into existence. Any particle that interacts with this field would, as a result, gain mass. The Higgs Field is omnipresent, and therefore cannot be manipulated. The only way to observe it is through the creation of the Higgs Boson by launching particles at each other in hadron colliders. However, the Higgs Boson is unstable, and thus quickly decays into smaller particles such as electrons or photons. The only way to detect it is to, according to CERN, "sift through the collision debris looking for the particles left behind by the Higgs Boson"[18]. The Higgs Boson is unique in the sense that it is the first-ever elementary particle associated with a scalar field[12], and thus has no spin. The Higgs Field does not act in a certain direction–it is indiscriminate. Rather, it lurks in the shadows and pulls the strings that allow the universe to operate from the background[18].

In 1993, the United Kingdom's Minister of Science, William Waldegrave, challenged physicists to come up with a reasonable and clear explanation of the Higgs Boson. The winner, physicist David Miller of University College London, received a bottle of quality champagne[19]. His explanation, utilizing the analogy of a cocktail party, was recently summarized in a Symmetry Magazine article by Kathryn Jepsen. She writes:

> "an average person could wander through the crowd with ease. But a more popular figure would be mobbed as soon as he or she entered the room...in this example, the party-goers represent the Higgs field, and the people walking through the crowd represent particles to which the field gives mass. A person who is significantly impeded by interested guests is like a particle given a large mass by the Higgs field. Excitation of the Higgs field is a Higgs boson...this kind of excitation might move through the crowd if a rumor spreads from one end to the other. People nearest the rumor-originator would lean in to hear it. They would then pass it along to their neighbors, drawing together a new clump of people, and then return to their original positions

[12] i.e. A field that solely measures magnitude, as opposed to a vector field that measures magnitude and direction.

> to discuss it. The compression of the crowd would move from one end of the room to the other, like a Higgs boson in a Higgs field"[19].

To this day, the Higgs Boson is a perplexing particle and is surrounded by many mysteries that physicists are hoping to uncover.

7 The Problem of Gravity

Gravity's exclusion from the Standard Model sticks out like a sore thumb. The Standard Model, introduced to answer the questions of the subatomic world, simply does not extend beyond the boundaries of the microscopic world. Gravity governs the macroscopic world, and is thus absurdly weak on a subatomic level. Moreover, it is a force present on an unparalleled scale and is responsible for the interactions between gigantic celestial bodies, whereas the other three forces are concerned with mere subatomic particles. As CERN affirms: "the quantum theory used to describe the micro world, and the general theory of relativity used to describe the macro world, are difficult to fit into a single framework"[16]. The whole concept of the Standard Model is to explain and compare the interactions between the four fundamental forces, and since gravity is so much more grand than the others, it simply cannot be compared to them. Furthermore, gravity is the only one of the four fundamental forces that does not have its own force carrier particle, at least, not one that physicists know of. Physicists have long predicted that a particle called the "graviton" is the force carrier particle for gravity, but this has yet to be proven[16]. For now, the Standard Model remains incomplete and will continue to be so, unless the conundrum of gravity is finally solved.

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