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Us and not Anti-Us

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Introduction

Why are we here? This is a vague question with many possible answers. From a biological standpoint, this question is asking how we evolved, and how life developed on Earth in the first place. From a philosopher's perspective, this question asks what the purpose of life is. From an astrophysicist view, this question asks what properties does the Earth and sun have that make Earth a suitable place for life. But one interpretation has not yet been asked; why are we us and not anti-us? When you look around, all you see is matter. Everything in our observable universe is made up of baryonic matter, that is simple up and down quarks and electrons. But for each of these particles there also exists an antiparticle that is essentially the same, so where did all of the antiparticles go? To discuss this topic, we first need to review the modern understanding of the fundamental physical world, as expressed in the Standard Model of particle physics.

The Standard Model

The current two main theories of how humans view the physical world are the theories of quantum mechanics and relativity, the study of the very small and very fast, respectively. To understand the smallest fundamental particles, the Standard Model was created, combining quantum field theory with special relativity to explain how the fundamental particles interact with each other and how three of the four fundamental forces work. Since its birth in the 1930’s, the Standard Model has become well established with a variety of experimentally confirmed particles. The Standard Model is now supported by thousands of physicists all across the globe (CERN Standard, 2012).

In the Standard Model, as seen in Figure 1., all matter is built from certain elementary particles. The two basic types of particles are quarks and leptons. There are six known quarks, grouped into three different pairs, the up and down quarks, the charm and strange quarks, and the top and bottom quarks, forming three generations of particles. The up, charm, and top quarks all have the same fundamental properties, except the quarks increase with mass from generation one, the up and down, to generation three, the top and bottom. This holds true for the down, strange, and bottom quarks as well. Each quark has a color, red, green, or blue, and quarks must always combine to form colorless particles where the red, green, and blue cancel out. There are also six known leptons, paired into generations one through three the same way that the quarks are grouped. In generation one are the electron and electron neutrino, generation two has the muon and muon neutrino, and generation three has the tau and tau neutrino. The neutrinos all have the same properties, as do the electron, muon, and tau. For both quarks and leptons, the generation three particles are the least stable and generation one particles are the most stable, so practically all of the world around us is made of up and down quarks, electron neutrinos and electrons (Close, 2004).

Of the four fundamental forces, gravity, electromagnetic, strong nuclear, and weak nuclear, gravity is not included in the Standard Model. Of the four forces, gravity and electromagnetic forces act over much larger ranges than the strong and weak forces, but gravity is the overall weakest force. Of the three forces in the Standard

Model, the weak nuclear force is the weakest and the strong force is the strongest. These three fundamental forces are mediated by particles called bosons. The electromagnetic force is controlled by photons, the strong force by gluons, and the weak force by W and Z bosons. It is likely that gravity is mediated by a boson called the graviton, but this particle has yet to be discovered. Also in this group is the recently discovered Higgs boson, which mediates the mass of particles (CERN Standard, 2012).

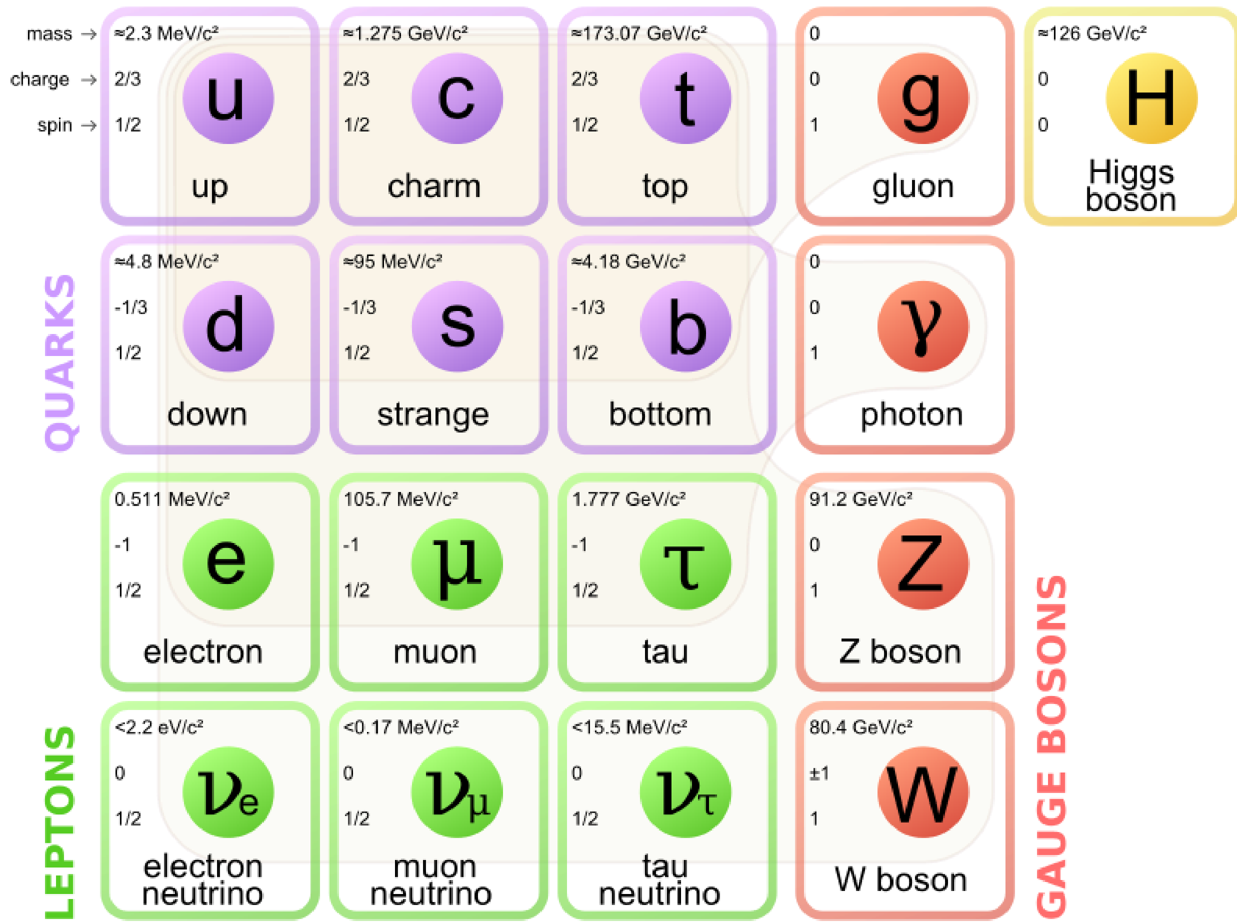

Figure 1. The elementary particles of the Standard Model. Quarks are colored purple, leptons are colored green, gauge bosons are colored red, and the higgs boson is in its own category. The leptons and quarks make up three generations, with generation one being the left column, and generation three being the column starting with the top quark. (Standard, 2014).

Antimatter

In 1928, a physicist named Paul Dirac wrote an equation that combined quantum theory and special relativity. This groundbreaking equation had one especially interesting quality. The equation required that for every particle, an identical particle of opposite charge could exist. These new particles were called antiparticles. This means that, in addition to all the above listed particles, there are also anti-quarks and anti-leptons. So just like an electron, there is an anti-electron, the positron, that has a positive charge. There are not anti-bosons because bosons do not have a charge and are not considered to be a part of matter. These antiparticles have been discovered and incorporated into the Standard Model (CERN Antimatter, 2014).

If antimatter is the same as matter, just with opposite charge, then where is all of this antimatter? Antimatter and matter have an intriguing property; when a particle and its antiparticle come together, both particles annihilate, converting all of their mass into energy. But this poses another problem of why there is any matter at all.

According to modern physical theory, there should not be any imbalance of matter and antimatter. At the start of the big bang, the baryonic number, which is a comparison of the amount of matter to antimatter in the universe, should be 0. If this were the case, with equal amounts of matter and antimatter, then all of these particles would have collided with each other and annihilated (Rodgers, 2001), leaving a universe of only photons, but about one particle in a billion survived this annihilation period, leaving the universe we see today. Most likely, some mechanism affected the process of baryogenesis, or matter creation, resulting in this imbalance. Imagine a normal coin spinning on its side. This coin would have a 50% chance of landing heads when it falls and a 50% chance of landing tails. But, on a table with hundreds of coins spinning, what if a special marble rolled around and every coin that the marble hit turned up heads. Most likely, the final result would end up with slightly more heads than tails, in the same way we have slightly more matter than antimatter. Physicists are now looking for that special marble (CERN The Matter, 2014).

It is possible that the universe began with a baryonic number greater than zero, that there was more matter than antimatter (Quinn, 1996). Unfortunately, there is no obvious reason why this would be, and a universe beginning with symmetry between matter and antimatter is more likely. To understand how a universe could begin with symmetry, but eventually become asymmetrical, we must first understand the principle of CP violation.

CP Violation

CP violation is part of a greater physical principle called CPT symmetry. CPT symmetry is a combination of three different principles, charge symmetry, parity symmetry, and time symmetry. Charge symmetry is the idea that any physical process should be the same for a particle of positive or negative charge. Parity symmetry is the same idea but with reversed spin. Spin is a fundamental property of particles. Time symmetry is the same idea but with reversing the direction of time. Physicists originally theorized that all three of these symmetries were always true, that you could reverse charge, spin, or time and still get the same results, but these symmetries were eventually proven to be false. Symmetries are needed to describe the physical world in a mathematical way, so that equalities can be written, because two things cannot be equal if equality does not hold in both directions. Early on in the Standard Model, it was realized that C and P symmetries could both be broken, so these symmetries were combined into CP symmetry. If CP symmetry holds, then if a charge symmetry is broken for a particle, where a particle is different if it has the opposite charge, then parity symmetry must also be broken, so that the particle is different with the opposite spin. In a way, this is like how two negatives can multiply to form a positive, two broken symmetries hold a true symmetry.

CP symmetry was believed to be always true until 1964, where a particle, the neutral kaon, was shown to break CP symmetry,referred to as CP violation. Now time symmetry was added to the other two, so that if CP symmetry is broken, then time symmetry also has to be broken, where a process is not the same going forwards and backwards in time. It is still believed that CPT symmetry always holds (Quinn, 1996).

There are two main different types of CP violations, indirect CP violation and direct CP violation. In indirect CP violation, first observed in 1964 with neutral kaons, particles fluctuate back and forth between particles and antiparticles in a process called mixing. The rate of the conversion of particles into antiparticles is different than the rate of conversion of antiparticles into particles, showing that the two types of matter are different. In direct CP violation, first observed in the 1990's, the actual rate of decay of a particle is different than the rate of decay for its antiparticle. Direct CP violation was first detected by the BaBar experiment at Stanford and the Belle experiment in Japan with B mesons, a particle composed of a bottom quark and an anti-down quark. Both experiments were called B factories, producing large amounts of B mesons and anti-B mesons, and then measuring the rates of decay. These experiments with B mesons showed that the Standard Model cannot explain why there is more matter than antimatter. (Rodgers, 2001)

Baryon asymmetry

One of the first theories for baryon asymmetry came from Andrei Sakharov in 1967. Sakharov stated three conditions that must be true for baryogenesis to occur. First, there had to be a point where the universe was not at thermal equilibrium, where certain reactions did not conserve the amount of energy in the universe. Second, during this time of thermal equilibrium, baryon number violations had to occur, but when thermal equilibrium was restored, the baryon number was frozen out, or fixed, at a value greater than 0. Third, CP violations must exist (Coles, 2001). Basically, Sakharov claimed that, at a certain point of the universe's development, the average temperature was high enough that baryon number violating processes occurred, but once the universe cooled enough, these processes stopped, leaving the universe permanently filled with more matter than antimatter. If these violating processes hadn't stopped, then the excessive matter would eventually have been balanced out. Sakharov's conditions are generally accepted in most theories of baryon asymmetry (Quinn 1996).

In the Standard Model, some CP violation is allowed under the Cabibbo-Kobayashi-Maskawa matrix. While resulting in some baryogenesis, this mathematical theory does not nearly account for the amount of matter observed in the universe. The amount of matter in the universe can be calculated by the expression nB/S, where nB is the baryon number density and S is the entropy density, mainly due to the 2.7 K background radiation. The observed nB/S = 10^-10 to 10^-11, but the calculations from the CKM matrix of the Standard Model gives a nB/S = 10^-26, not nearly enough matter (Quinn, 1996).

Grand Unification Theories

Grand Unification Theories, commonly referred to as GUTs, are theories that adjust or replace the Standard Model by unifying all of the four fundamental forces into one force. This grand unified force was transmitted by massive bosons, but because the temperature is much lower now than near the big bang, the grand unified force has been suppressed into four forces. The universe's average temperature is not great enough to allow for the stability of massive particles (Quinn, 1996).

GUTs usually allow for baryon number violation because the massive bosons of the combined strong and weak force could have mediated baryon number violating processes that no longer occur. As the universe cooled, the grand unified force split into gravity, the strong nuclear force, and the electroweak force. At this point, the process that was causing baryogenesis has stopped because the massive bosons have been replaced by smaller bosons, but processes could still occur that balance out the baryon number, destroying excessive matter. When the electroweak force split into the electromagnetic and weak nuclear forces, the balancing processes also had to stop, so that not all of the excessive matter was converted into other forms (Quinn, 1996).

Unfortunately for GUT, this massive bosons that is needed to mediate the grand unified force has not yet been discovered and would require substantial energies to create. While GUT could still be a solution to baryon asymmetry, other physicists have attempted to use dark matter to explain this perplexing situation.

Dark Matter Theories

Dark matter, or unexplained curvature of the universe, is thought by physicists to be one or multiple unidentified particles. In this perspective, DM is typically referred to as Weakly Interacting Massive Particles, or WIMP. Predictions suggest that there is more dark matter than matter, that the universe is comprised of 4.9% matter and 26.8% dark matter (Boucenna, 2014). Because of these relatively similar abundances, many physicists have tried to connect the two. The main theories connecting DM to baryogenesis attempt to assert that either DM and baryonic matter are connected through some sort of collision or decay process, or that the presence of DM boosts the baryogenesis already in the standard model.

The main reason that DM is thought to be related to the observed baryon asymmetry is a phenomenon called the WIMP miracle. At a point in time, where the dark matter density froze out and became fixed at a density of 26.8% of the universe, the density of dark matter was proportional to the abundance of weak interactions.

Unless the WIMP miracle is a major coincidence, dark matter is most likely a weakly interacting particle, whose density was fixed after the split of the electroweak force just like the baryon number was fixed after the split of the electroweak force (Boucenna, 2014).

In the theory of WIMPy baryogenesis, if dark matter is weakly interacting, than some dark matter could annihilate with itself in a process that satisfies Sakharov's conditions and favors baryon generation over antibaryon genesis. In this case, to have symmetry, baryons would also be required to have a process that either converts baryons into dark matter or into antimatter. But if this is also true, these two processes would have balanced out leaving the net baryon number to still be 0. For baryon asymmetry to work, the process destroying baryons would have to freeze out before the process converting DM to baryonic matter. A large period of time would have to separate these two events to allow for the current observed baryon number. The most likely reason that this theory could work is if a process converted baryons into an exotic massive antiparticle. As the universe cooled, the generation of the massive antiparticle would have stopped long before the generation of baryonic matter from dark matter. This theory would be easy to confirm if a massive antiparticle was discovered (Boucenna, 2014).

Another theory involving the WIMP view of dark matter is called the Meta-stable WIMP. In this concept, there are two main categories of dark matter, stable WIMPs and unstable WIMPs. After the dark matter density froze out, the unstable WIMPs could decay into baryonic matter in a way that violates CP symmetry. If this were the case, then the equation (see Figure 2.) can predict the current amount of baryonic matter from the density of unstable WIMPs (Boucenna, 2014).

$$Y_B(T_0) \approx \epsilon_{CP} \int_{T_0}^{T_D} \frac{dY_{Y_2}}{dT} dT \simeq \epsilon_{CP} Y_{Y_2}(T_f)$$

Figure 2. An equation describing the current baryonic density, YB(To), using the ratio of matter to antimatter, eCP, the density of the decaying WIMP, YY2, and the average temperature now, To, and at the freeze out, Tf.

Other theories not based on the weak interactions of dark matter are referred to as Asymmetric Dark Matter Theories. These theories evaluate the ratio of dark matter to matter and usually assume that dark matter is asymmetric in the same way that baryonic matter is. One idea is that a massive particle existed early in the universe that decayed into dark matter and matter, so that the asymmetries of both matters were balanced. Another idea is that a not yet discovered process caused dark matter asymmetry, which then resulted in baryon asymmetry through a decay process (Boucenna, 2014).

Finally, in the theory of electroweak baryogenesis, dark matter is assumed to amplify the amount of baryogenesis generated in the standard model by amplifying the effect of the higgs boson on matter. For this CP violation to occur, the higgs boson would have to be very light, unfortunately lighter than the current observed mass of the higgs boson. Calculations show that for the observed mass of the higgs boson, the predicted amount of dark matter is significantly less than the observed amount of dark matter. This contradiction could be resolved if there exists more particles in the higgs sector, especially if there is another lighter higgs boson that could have mediated the larger density for dark matter. In this theory, dark matter and baryonic asymmetry are related, but dark matter is affecting baryonic matter and not the other way around (Boucenna, 2014).

Conclusion

With an understanding of the Standard Model of particle physics and antimatter, physicists have attempted to explain the observed baryon asymmetry of the universe. Many of these theories combine an explanation of baryogenesis with other physical theories, such as GUT or dark matter. Although no decisive evidence has yet been revealed on this topic, these theories are all provable through different mathematical manipulation and particle discoveries in large particle colliders. In the coming decades, we may truly know why we are us and not anti-us.

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