An Overview of the Antimatter-Matter Asymmetry Problem

Jaahnavi Maheshwari[1], Davio Cianci[2]

[1]Student, Inventure Academy
[2]Professor, Columbia University

Abstract

This literature review delves into the heart of the Matter-Antimatter Asymmetry Problem, a fundamental puzzle that challenges our understanding of the early universe and the dynamics of particle interactions. A few new innovative theories and experimental investigations exist to approach this problem and are elucidated in this paper, specifically charge-parity violation (CPV) and Baryogenesis. The paper begins with exploring the historical development of the Matter-Antimatter Asymmetry Problem. It then examines the theoretical constructs necessary for generating the observed imbalance, such as Sakharov's conditions. This is followed by an analysis of the experimental evidence and ongoing research efforts, coupled with advancements in theoretical frameworks of CPV and baryogenesis mechanisms that offer promising avenues to unlock the secrets of matter-antimatter asymmetry. However, these theories still need to fully answer the question of the asymmetry problem, pushing us to explore the potential extensions to the Standard Model that may provide a resolution.

Introduction

One might wonder why scientists thought about creating entirely different forms of matter; Where in the world would the idea of these particles, which do not seem to concern our daily lives, even come from? Science has always been about asking questions and conducting investigations to gain even the slightest insight into the query raised.

One of these basic questions revolves around the creation of the universe. Scientists have posed many theories that indirectly aim to answer this question. Despite the initial expectation of equal amounts of matter and antimatter created during the Big Bang, the present-day cosmos is overwhelmingly composed of matter. This striking asymmetry, enabling our existence, forces us to reevaluate existing theoretical frameworks and look for opportunities beyond.

1.1: The Origin of the Antimatter Idea

In the quest to find explanations and theories that explain our observable world, we long relied on Newtonian mechanics which laid the foundation of classical physics as we know it today.

This understanding seemed to be universal until Albert Einstein enlightened us about the concept of relativity in 1905. Meanwhile, another scientist, Erwin Schrödinger, conducted experiments in quantum mechanics in 1935 that changed our understanding of how quantum states change over time and helped predict the behaviour of quantum systems. Given the limitations of Newtonian physics, such as the constraints on the mass and speed of the object, and the potential of Schrödinger's theories, physicists hoped to develop a way to make Einstein's theory of relativity compatible with Newtonian mechanics, encouraging the quest to make the Schrödinger equation work for relativity.

In 1928, Paul Adrien Maurice Dirac, a British theoretical physicist, formulated what is known as the 'Dirac equation' today, which incorporated ideas of special relativity and energy.

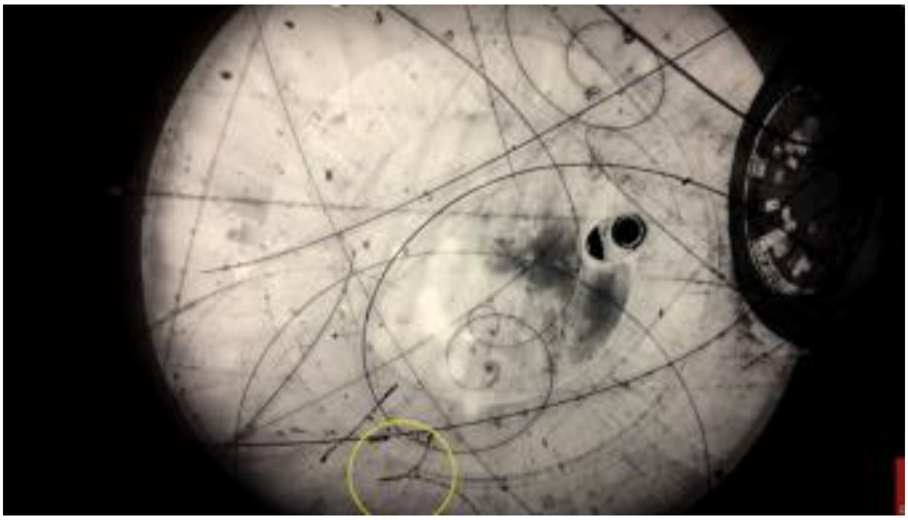
In regards to a particle in a box, the difference between Schrodinger and Dirac's equations was that the former yielded only positive energy states electrons could be in while the latter also gave negative energies associated with electrons. This was perplexing since electrons prefer being in the lowest energy state possible and a negative energy state would imply that the electrons would reposition there.

Instead of modifying his equation, Dirac hypothesised that these negative energy areas are already filled with electrons that might move up to positive energy states when excited by photons, creating a deficit of negative charge. This region has one more positive charge in it now, this is the positron — an antiparticle. This formed what he called an electron-positron pair. Hence, for electrons to exist, there must be a positron and 2 photons must create this pair to account for the masses.

Dirac's theorisation of the existence of antiparticles came long before they were proven by experiments in the Bubble chamber later on.

1.2: What is matter/antimatter?

In 1932, Carl Anderson, an American physicist, confirmed the existence of antimatter through his bubble chamber experiment. A bubble chamber is essentially composed of compressed liquid in a vacuum amidst certain electric and magnetic fields; when a particle passes through this dense vapour, it collides with the vapour's molecules, causing them to ionise by losing their electrons. The path travelled by the particle leaves a trail of ionised electrons whose energy causes the vapour to bubble. By photographing how these particles deflect/ spin in the presence of a magnetic field, Anderson identified a particle with the same mass but opposite charge as an electron: a positron.



An image of a bubble chamber demonstrating pair production
(Figure 1)

Observing these bizarre particles, which had the same mass as their matter counterparts yet were different in certain properties like charge, took the scientific community by storm. Scientists wanted to know everything about this exciting new particle, prompting a search for ways to create antimatter. One known source of antimatter was gamma-ray spectra and cosmic rays, created by electrons accelerated by strong electric fields in the clouds. However, capturing and preserving these particles seemed tedious. Scientists instead used about a million electron volts of energy to accelerate photons in a bubble chamber. Here, they saw that this photon split into two particles that spun in opposite directions in the magnetic field forming a clear vertex between them.

Photons could produce an antimatter and matter pair, and as symmetry would predict, these pairs would annihilate and produce energy in the form of photons when they came together. Scientists have measured the properties of particles and antiparticles with extremely high precision and found that both behave identically. Antimatter and matter interact similarly, so if the universe created equal amounts of matter and antimatter then they should have all annihilated on contact.

Naturally, a pressing issue arises. How do we still exist? Why is the universe not solely composed of energy?

1.3: Why matter over antimatter?

Antimatter particles can be produced using ultra-high-speed collisions in huge particle accelerators such as the Large Hadron Collider, which can create antiprotons formed from antiquarks. These can form anti-atoms that makeup antimatter.

At most, scientists have managed to create antihydrogen, the antimatter twin of the element hydrogen. The most complex antimatter element produced to date is antihelium, the counterpart to helium. The Tevetron experiment at Fermilab used this particle accelerator to study high-energy particle collisions and in doing so produced over 15 nanograms of antimatter; the largest producer of antimatter yet.

We are made of matter; the things around us comprise electrons and protons that form atoms assembling our matter. All our laws of physics have held for a matter-dominated universe, leaving us with one of the biggest open questions in physics: where did all the antimatter go?

Perhaps antimatter and matter separated at the beginning of the universe, creating corresponding antimatter planets and systems. However, in this case, we would feel the presence of a universe of antimatter due to the energy produced in the barrier of the two worlds between matter and antimatter. Another explanation for this absence of antimatter hints at the possibility that the laws of physics may have had a preference towards matter over antimatter.

In the first moments after the Big Bang, only energy existed. As the universe cooled and expanded, particles of both matter and antimatter were produced. A phenomenon could have occurred that created even the slightest imbalance between these particles. For example, for every billion antimatter particles created, a billion plus one matter particles may have been produced and the annihilation of these would result in enough matter particles that formed our observable galaxy today.

There are many theories explaining this phenomenon. It may have been the presence of ‘unusual particles’ that decayed at the start of the Big Bang leaving a lot of matter without an antimatter counterpart. Some have postulated that tiny black holes might have evaporated into a certain entity that in turn decayed into matter. These events must somehow be biased towards matter under certain conditions that violate the baryon number and in doing so these interactions must violate certain symmetries and must happen in a very sudden way, these will be elucidated further in this paper.

Why symmetry? How does it arise?

2.1: Why is symmetry presumed?

Why did we base the fundamental system that governs our universe on symmetry?

Symmetry has been prevalent in all our observations of nature. In physics, we notice symmetry in simple conservation laws: when we add the total drop in potential across components in a closed loop it equates to the EMF of the battery. Similarly, symmetry is also observed in mathematics when equations cancel out when equated. In our pursuit to recognise and appreciate symmetry, we identify patterns to simplify problem-solving.

It is through the eyes of symmetry reinforced by special relativity and quantum mechanics that scientists believe the universe created equal amounts of matter and antimatter during the Big Bang. The difference in the behaviour of antimatter and matter in the earlier conditions of the universe may have resulted in the apparent asymmetry we see today.

Soviet scientist Andrei Sakharov posited three conditions which would allow for a matter-antimatter asymmetry to flourish.

2.2: Sakharov's conditions

Sakharov's conditions outline the environment in which inconsistent behaviour of antimatter and matter can ultimately yield a matter-dominated universe.

The conditions are as follows:

- Baryon number must be violated;
- Charge-parity symmetry must be violated;
- The universe does not exist in a state of thermal equilibrium.

2.2a: Non-conservation of Baryon number:

Baryons are subatomic particles, like protons and neutrons, made of 3 quarks — the fundamental building blocks of matter. There are 6 'flavours' of quarks and each has its corresponding antiquark, which makes up antibaryons.

A violation in the Baryon number seems only necessary to produce an excess of baryons over antibaryons: if the baryons exceed antibaryons, even by a small quantity, then the ability of each baryon to 'pair up' with an antibaryon reduces, preventing the possibility of total annihilation. There must be irregular interactions in the form of CP(Charge-Parity) violation to create this imbalance in the Baryon number. If somehow a mechanism evolved that favoured matter over antimatter during the evolution of the universe, then we would likely observe this asymmetry.

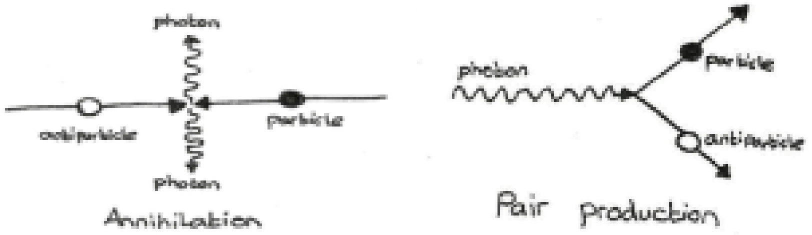
2.2b: Violation of CP Symmetry

An aspect of an object is said to have symmetry through a transformation if that aspect remains unchanged under that transformation. Say, for example, we have a sphere. If we execute an operation such as rotating it at some angle around a central axis; it remains the same shape, we say the sphere shows rotational symmetry.

There are 3 different types of transformation we observe in our universe that are exhibited when a series of operations take place on a particle's state. Just like a change in the reference frame is characterised by a Lorentz transformation, C, P and T refer to charge, parity and time transformations.

- Charge conjugation is an operation that reverses the electric charge of particles. For example, the charge conjugate of a positively charged particle would be a negatively charged particle. Say you take two particles that are positively charged then they repel. When these charges are reversed, they will still repel each other.
- Parity is a spatial inversion operation that flips the coordinates of particles, effectively turning left-handed into right-handed configurations and vice versa.

- Time reversal is a mathematical operation of replacing the expression for time with its negative in formulas or equations so that they describe an event in which time runs backwards or all the motions are reversed. The implication is that the fundamental laws of physics apply uniformly in both scenarios, making the reversed event indistinguishable from the original in terms of time. For instance, electron-positron pair production from photons and pair annihilation to form photons follow reversal time symmetry.



Feynman diagram illustrating time-reversal symmetry

A particle and its antiparticle are simply CP transformations of one another. The mechanism required to favour baryon production over antibaryon must naturally violate C and CP transformations since a bias must be created in the laws of physics that does not treat antimatter and matter the same way in interactions.

In 1956, it was observed that weak nuclear forces strongly violated CP, since they only acted on a matter particle if it was spinning counterclockwise and on an antimatter particle if it was spinning clockwise.

In 1964, it was believed that performing simultaneous C and P transformations (performing a CP transformation) would result in symmetry, However, this too was disproved when kaons were observed to spontaneously become antikaons which we will explore further in the paper.

Nevertheless, this violation gave us an insight into how matter could be treated differently. However, there is not enough of this defiance of CP symmetry to resolve the quandary of matter dominance.

2.2c: Reactions out of thermal equilibrium

The process that causes this imbalance in the universe must happen in a rapidly changing and volatile environment; if it was a slow steady process, then interactions would work both ways reaching equilibrium. Hence, a universe which deviates from thermal equilibrium would facilitate an asymmetry of matter and antimatter. In other words, the conditions for creating a baryon asymmetry are most effective when the relevant interactions occur out of equilibrium.

It is hypothesized that this environment was emanated by a phase transition in the early universe. In cosmology, phase transitions refer to a radical change over time from the hot matter-dense universe to the universe we see today. For example, the QCD (quantum chromodynamics) phase transition refers to when quarks were first bound together to form protons, this was also out of equilibrium.

Perhaps an unfamiliar substance in the universe fell out of equilibrium just 1/100th of a second after the Big Bang and started decaying differently, ejecting matter instead of antimatter. However, it is difficult to test any idea regarding this, as we cannot reproduce the exact conditions for these interactions to take place.

Sakharov’s conditions tell us that for the universe to end up with more matter than antimatter, all these three conditions need to be violated simultaneously. It is most likely these conditions were met in the very hot and dense state shortly after the Big Bang that allowed the preference of matter.

Sakharov’s conditions can inspire scientists with a few directions to begin looking for an explanation. This leaves us wondering if there is a fundamental difference between how matter and antimatter interact with the universe or if perhaps there was merely an asymmetrical initial condition. We're going to spend some time talking about this in Baryogenesis and CP Violation.

Analysis of Baryogenesis

3.1: Baryogenesis

One renowned theory to explain this asymmetry is baryogenesis. This theory explores a change in the initial condition: a beginning with asymmetry itself.

Baryogenesis is the physical process that is hypothesised to have taken place during the early universe to produce baryonic asymmetry. According to baryogenesis, the baryon asymmetry in the universe was produced at very high temperatures; heavy right-handed neutrinos decayed in a manner that caused lepton number violation. This generated a change in the electroweak forces (electroweak phase transition), where the electroweak symmetry was broken. The weak force which was long-ranged became short-ranged, and the W and Z bosons which were massless, became massive and acquired mass, thus generating a baryon asymmetry.

It therefore seems that the universe is fundamentally matter-antimatter asymmetric. While the above considerations put an experimental upper bound on the amount of antimatter in the universe, strict quantitative estimates of the relative abundances of baryonic matter and antimatter may also be obtained from standard cosmology.

3.2: What is the lepton/ baryon number?

Leptons are the building blocks of matter and their interactions play a crucial role in the dynamics of particle physics. Leptons include particles such as electrons, muons, tauons, and their corresponding neutrinos. The quantity of each type of lepton in an interaction is described by a Lepton Number, which is equal to the number of leptons minus the number of antileptons. The lepton numbers are assigned as follows:

- Electron Lepton Number (L_e): Assigned to electrons and electron neutrinos.
- Muon Lepton Number (L_μ): Assigned to muons and muon neutrinos.
- Tau Lepton Number (L_τ): Assigned to tau particles and tau neutrinos.

Leptons interact mainly via the electromagnetic force and the weak nuclear force. The conservation of the lepton number is a principle that states the total lepton number should remain constant in any particle interaction or decay process. In other words, the sum of the lepton numbers before and after a particle interaction should be the same. This plays a role in understanding and predicting the outcomes of various particle interactions, and it is an important aspect of the broader conservation laws in particle physics.

Neutrinos can mix between their different flavours (electron, muon, tau) as they propagate in a phenomenon known as neutrino oscillation. While the total lepton number (the sum of L_e, L_μ, and L_τ) is still conserved in these processes, individual lepton flavours may change. This calls for a violation of Lepton number.

As mentioned earlier, baryons are a class of subatomic particles that are made up of three quarks. Quarks are elementary particles that combine to form composite particles, and baryons are one such type of composite particle. The most well-known baryons are protons and neutrons, which comprise atomic nuclei.

Similarly, the Baryon number is a quantum number used in particle physics to quantify the number of baryons in a given system.

The baryon number (B) is assigned as follows:

- Baryons (e.g., protons and neutrons) have a baryon number of +1.
- Antibaryons (antiparticles of baryons) have a baryon number of -1.
- Non-baryonic particles (e.g., electrons, neutrinos) have a baryon number of 0.

Further details about baryons and baryon number violations have been described in a prior section.

3.3: Experiments

There has been no direct evidence of baryogenesis as of now. However, most grand unified theories (GUTs) require a baryon violation to occur for any asymmetry to take place. The standard model allows for some small amount of baryon number violation, which would have taken place in the early universe during phase transitions, but this is nearly not enough to explain the discrepancy we currently see.

To provide a larger source of baryon violation, some scientists are trying to provide evidence for the existence of neutron-to-antineutron oscillation. This finding could go a long way toward answering the matter-antimatter asymmetry problem by indicating a baryon number violation and that matter itself is unstable. It could indicate the process through which matter evolved from an initial 0 baryon number in the early stages of the universe. The experiment plans to exploit slow neutrons to study their oscillations and derive values needed to sustain the theory.

So far, experiments at Fermi lab, involving a series of particle collisions, found that the amount of generated matter was approximately 1% larger than the amount of generated antimatter.

Whether this disparity was innate to the universe, as baryogenesis suggests, is not yet known.

3.4: Analysis

The theory of baryogenesis intrinsically questions our understanding of physical interactions and symmetry as we know it today. There is an overall lack of direct experimental verification of the specific mechanisms involved in baryogenesis because recreating the early moments of the universe, where baryogenesis is presumed to have occurred, in an experimental setup is challenging due to the extreme conditions and the lack of direct observational data.

The complexity of the early universe introduces uncertainties in theoretical models of baryogenesis. However, it is important to emphasise that the understanding of baryogenesis is dynamic and an ongoing process in theoretical and experimental particle physics.

CPV Theory and Experiments

4.1: What does CPV mean to the antimatter matter asymmetry?

As mentioned earlier, C is a transformation of charge and P is a transformation of parity. Simply put,

- C switches the sign of electric charge as in $Q \to -Q$.
- P switches the sign of spatial coordinates as in Left-handed → Right-handed or vice-versa

The charge, parity and time transformations, if perfectly conserved, and given symmetrical initial conditions, would result in equal quantities of matter and antimatter that would annihilate each other as per the standard model, leaving no matter behind.

The universe made of matter exists, so this is not the case. There must be a violation of the operations we discussed before that would yield an unequal result compared to the initial condition, explaining the overrepresentation of matter in the universe.

Most scientists believe that interactions under all four forces (strong, weak, electromagnetic and gravitational) must maintain CPT symmetry (remain invariant via these transformations) for the laws of conservation of energy to hold. In weak and strong interactions we know that T symmetry is maintained, hence we must also have CP symmetry. However, this has proven to not be the case.

The violation of C symmetry alone is not sufficient. We need to have a P violation at the same time. To illustrate how transformations build upon one another, let us consider two different rotations. For example, an object can be rotated around one axis causing it to end up in a completely different position. This is not a symmetry. However, with a different additional rotation, we can maneuver the object to its original state; The combination of these two rotations will be symmetrical.

An antiparticle is simply a CP transformation of its particle counterpart or applying a CP transformation would change a matter particle to its antimatter counterpart or vice versa. CP violation is allowed in the standard model up to some parameters. The standard model allows for a tiny amount of CP violation without any disagreement with conventional laws.

4.2: Evidence for CPV:

Evidence found for CP violation supports the allowed violation according to the SM. These phenomena are described further below.

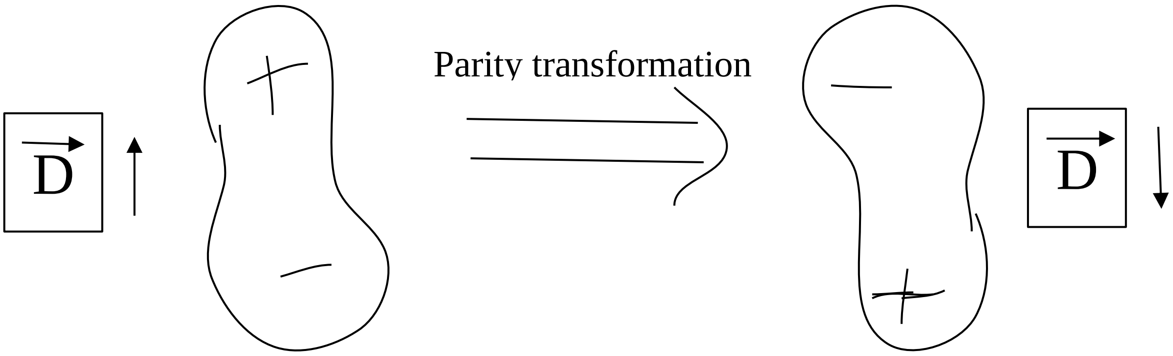
4.2a: Neutron Electric Dipole Moment

The electric dipole moment (EDM) of a particle or system is a measurement of the distribution of charges across the volume of the particle. A neutron is neutral, but it is made up of charged quarks; the spread-out charges will total charge to 0. Therefore, the EDM should also be zero. However, this is not the case because these non-zero charges are not evenly spread. Experiments studying the EDM of a neutron have found that the measurement would result in a nonzero value, which suggests a violation of time reversal and CP symmetry.

To illustrate this consider the following:

➔ First, we apply a parity transformation:

- Reversal of spatial coordinates
  X→ -X, Y→ -Y, Z→ -Z.
- The electric displacement(**D**) vector's components will flip



- Angular momentum will remain the same:

$$\vec{r} \times \vec{p} = \vec{J}$$
$$(-\vec{r}) \times (-\vec{p}) = \vec{J}$$

➔ Now, if we apply a time reversal transformation:-

- The EDM does not change, since the space is not affected.

- Angular momentum does change since the velocity is now negative:

$$\overrightarrow{r} \times (\overrightarrow{-p}) = \overrightarrow{-J}$$

Hence, we see an asymmetry in the P and T transformation when the vector D is nonzero.

4.2b: Neutral Kaon system:

In the search for whether the weak force, like the strong and electromagnetic forces, obeyed P symmetry, physicists Yang and Lee proposed an experiment that showed how beta decay, dominated by weak forces, violated P. However, it remained invariant under CP symmetry. Hence, the notion of CP and T symmetry in weak interactions was favoured until the first evidence of CP violation was observed in the decay of neutral Kayons (K mesons) in 1964 with the Fitch-Cronin Experiment.

The experiment involved neutral K-mesons which are made up of a combination of strange or antistrange quarks and an up or down quark. This gives them a property called strangeness, which can be thought of as a quantum number associated with certain types of particles, making them suitable for demonstrating CP violation.

Neutral kaons have a positive strangeness, hence antikaons must have an opposite strangeness. However, experimental evidence showed that the neutral and antineutral kaons decay into a pion pair or triplet which does not have any strangeness; hence strangeness is not conserved.

To explain this, scientists posited that kaons are a mixture of two states: K_1 and K_2, which both have CP (magnitude) = 1. However, K_1 decays into 2 pions and K_2 decays into 3 pions. According to fundamental physics, decays with greater changes in mass occur more readily, so the K_1 decay happens 100 times faster than the K_2 decay thus we can say that K_1 is K_{short} and K_2 is K_{long}. This can be denoted as Eigen states below:

$$K_1 = K_S^0 = \frac{K^0 + \overline{K^0}}{\sqrt{2}}$$

$$K_2 = K_L^0 = \frac{K^0 - \overline{K^0}}{\sqrt{2}}$$

Applying this knowledge, Cronin and Fitch sent a beam of koans through a 57-foot collimator to measure the rate of decay of the kaons. Since K_1 decays much faster, after a sufficient amount of time, we can expect the beam to comprise only K_2. If K_1s are found in the beam it would indicate a flip from K_2 to a K_1, and the CP for the particles would have flipped from -1 to +1, thus violating CP. In the decay of K_2, the decay angle θ can rarely be 0, while in K_1 this angle θ has to be 0, owing to the number of final-state particles (two or three respectively). The experiment was designed to obtain the momentum, mass and timing information, and calculate the decay angle θ. It showed that for every decay of K_2 into three pions, there are (2.0±0.4)×10-3 decays into two pions.

This suggests an indirect CP violation if we consider ‘meson mixing’, where K_1 and K_2 oscillate between one another; or a direct CP violation where K_1 and K_2 contain a very small amount of each other.

4.2c: Neutrinos

A neutrino is an elementary particle belonging to the same category of elementary particles, leptons, as electrons, muons, and taons. They are often observed and investigated with water Cherenkov and liquid scintillator detectors which utilize large volumes to increase the chance of weak interactions. It was found that neutrinos mainly undergo weak interactions and are electrically neutral, allowing them to pass through matter. These particles are exceptionally light particles that scientists previously thought of as massless. We can produce neutrinos in nuclear reactions and radioactive decay and can be created in particle accelerators and nuclear reactors.

Neutrinos can come in unique ‘flavours’: electron neutrinos (ν_e), muon neutrinos (ν_μ) and tau neutrinos (ν_τ). They exist as a mix of all three types at once, and as neutrinos propagate, their proportions keep changing. They can undergo flavour oscillations, changing from one flavour to another as they go through space. A tiny anomaly in these oscillations could hold the answer to the asymmetry question.

The standard model does not provide a mechanism for neutrinos to possess mass, yet for neutrinos to oscillate they must be composed of a mixture of different mass states: ν_1, ν_2, and ν_3, in a fixed ratio for each flavour.

$$|\nu_\alpha\rangle = \sum_i^3 U_{\alpha i}|\nu_i\rangle$$

Hence, a neutrino may originally be a muon neutrino but due to its fabric of mass states, it can have a non-zero probability of being measured as an electron neutrino.

The Pontecorvo–Maki–Nakagawa–Sakata matrix (PMNS matrix), also known as the lepton mixing matrix or neutrino mixing matrix, describes the proportions of these mixing mass states:

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

All neutrinos (matter) are very light and left-handed (have clockwise spin) while all the antineutrinos are heavy and right-handed. We see from this that the light and heavy masses are inversely related and this can only be possible if the neutrino is its own antiparticle, a property exhibited by Majorana particles.

Normally we would expect antineutrinos and neutrinos to behave the same way according to the standard model. However, this is not the case. Detecting this deviation in behaviour in the way neutrinos and antineutrinos change flavours at different rates beyond the standard model could give us an insight into the asymmetric universe. When the CP violating phase (a parameter that denotes the amount of CP violation) in neutrino oscillation is non-zero, then the antineutrino and neutrino could switch between each other, suggesting that an initial neutrino, a matter particle, could become an antineutrino, an antimatter particle, due to the mixing of states.

Scientists believe that this lepton asymmetry or leptogenesis can lead to a difference in baryon number, indirectly justifying the baryon asymmetry problem. This can be done when the baryon and lepton numbers are individually violated, but the overall combination of baryon and lepton numbers is conserved. These are observed in the neutrino interactions concerning Sphaleron processes which refer to a quantum field theory associated with the transition region between the symmetric and broken phases of the electroweak theory.

This lepton asymmetry, through the sphaleron process, can be exemplified by looking at the decay of neutrinos when they populated the hot, primordial universe. If there were super-heavy neutrinos their antineutrino counterparts could have decayed distinctly, creating enough CP violation (due to their heavy masses) to generate the abundance of matter we see today, hence saving us from our possible annihilation.

4.3: The strong CP problem

Another puzzling matter in physics is that CP violation has only been associated with or accepted in weak forces. However, it has never been observed in strong forces. In the weak force interactions, the symmetries of C, P and T are violated individually, and the combinations of CP, PT and CT are violated.

However, all 3 CPT have never been violated.

Similarly, interactions with the electromagnetic force conserve all types of symmetries (abelian characteristic). Thus, we see the standard model allows and restricts certain interactions. The standard model allows C and P violation in both strong and weak forces, but it has only been seen in weak forces. This refers to the ‘Strong CP problem’ because the absolute lack of CP violation among strong force interactions implies issues with the standard model itself.

A theory proposed by Roberto Peccei and Helen Quinn (Peccei-Quinn mechanism) elucidates the conditions in which CP violation is suppressed in strong interactions. It predicts the existence of a new particle: axion; an abundant light and neutral particle. The discovery of axions alters a certain value (theta parameter) that is responsible for CPV making it almost 0, effectively hiding it and ensuring CPV is negligible in strong force interactions. The strong CP problem is an especially interesting puzzle because it describes the absence rather than the existence of something that is observed and so thoroughly expected.

4.4: Analysis

CP violation is evident and permitted even by the standard model. However, there is not enough of it to explain the asymmetry in the universe. I feel CP violation is a critical operation that should have occurred in any circumstance to initiate an asymmetry.

Theorists have gone far beyond the standard model, distorting the fundamental understanding, to find ways to make CP violation more prevalent and explain the cosmic asymmetry. The Grand Unification theory (GUT) goes beyond the standard model by unifying the strong, weak and electromagnetic forces at high energy and theorises a splitting of the forces when the system cools, thus initiating an asymmetry and creating distinct particles linked with these forces.

Several such theories have been proposed devising completely different frameworks to govern our quantum world. The only thing impeding the tangibility of these theories is the lack of an experimental apparatus to test the predicted energy states for each of these forces. Nevertheless, GUT has the potential to explain several mysteries in physics, and hopefully, future experiment setups may provide indirect evidence for their existence.

Summary

The antimatter-matter asymmetry is a fundamental puzzle in particle physics and cosmology that aims to explain the observed dominance of matter over antimatter in the universe. According to the principles of symmetry and conservation of baryon number and the standard model, equal amounts of matter and antimatter should have arisen at the beginning of the universe’s existence.

Experiments in particle accelerators such as the Large Hadron Collider (LHC) reveal subtle differences in the behaviour of B mesons and their antiparticles, which can be seen in the form of violations of CP (charge parity) symmetry. The standard model includes the possibility of some CP violation in weak and strong interactions. However, this is not nearly sufficient to explain all the observed asymmetry. The two main theories discussed in this literature review, CP violation and Baryogenesis, have come the closest in attempting to answer this question. The main difference between them is that while baryogenesis proposes an initial asymmetry at the formation of the universe itself, it overlooks several elemental laws of physics; CP violation, on the other hand, theorises a way that the initial symmetry could have turned a bias towards matter, but the amount of CPV observed is just not enough to create the imbalance we see today.

Though the paper displays these theories as distinct from one another, in reality, both CPV and baryogenesis could have occurred since neither theory has proven to be true with accurate explanations. Current propositions are attempting to incorporate the idea of CPV and Baryogenesis into a single mechanism. Further, the paper briefly discusses how leptogenesis could have caused the possible baryon number violation through neutrino decay.

Another important issue the paper brings to light is the strong CP problem, which highlights the fact that CPV is only observed in the weak sector, even though the standard model also predicts its existence in strong forces. Undoubtedly, there are required modifications to be made in the standard model, which have so far proven successful in predicting interactions between constituent matter particles like quarks or leptons and the electromagnetic, weak and strong nuclear forces. Scientists are using this opportunity to investigate approaches beyond the standard model.

Thinking forward…

After understanding the complexity of this problem, several questions are still left unanswered.

Theories point towards an explanation outside our existing fundamental interpretation of particle interactions and the quantum field theory. These approaches also include the prospect of a mirror universe of antimatter or certain topological defects in the galactic fabric such as cosmic strings, monopolies or domain walls that could have occurred during the phase transition of the universe.

We are compelled to deliberate out of the common situations, distorting our understanding of nature. For instance, what would happen if symmetry itself breaks down? Why do neutrinos exhibit single-handedness and where do they get their masses from if not the Higgs field that is responsible for the mass mechanism of particles?

Other questions like that of dark matter, supersymmetry, and axions demand a further reexamination of our conventional premises. These possibilities hint at a universe with unified forces, thus supporting the GUT theories. For example, supersymmetry provides a solution to the problem of different scales of particle masses by introducing a corresponding bosonic ‘superpartner’ for each fermion (sfermion) and the same for every boson, resolving the problem

by providing an origin of a neutrino’s mass and also posing as a candidate for dark matter.

Furthermore, the existence of the ‘axion,’ an extremely light, abundant particle with no charge, appears to provide justifications for the strong CP problem and the creation of dark matter caused by the oscillations of the axion field due to spontaneous symmetry breaking. Another peculiar implication of CP violation is that protons must decay- the lightest particles with a baryon number or the most stable particle could be decaying. However, this is happening very slowly, and the effects are visible in the Deep Underground Neutrino Experiment (DUNE) which searches for proton decay, bound-neutron decay and neutron-antineutron oscillations by testing the law of conservation of baryon number.

Further explorations might defy or doubt our present familiarity with the topic in question. However, through the right developments in theoretical and experimental physics, and with a little help from nature, we just might find out.

Conclusion

Research to understand the problem of antimatter-matter asymmetry is ongoing, with experiments in particle accelerators and theoretical developments through GUT theories seeking to understand these fundamental forces and particles in more detail, by exploring various possibilities.

A variety of ongoing and planned experiments continue to explore the mysteries surrounding the matter-antimatter imbalance in our universe. However, it remains one of the biggest open questions in physics.

REFERENCES

1. https://en.wikipedia.org/wiki/Baryon_asymmetry
2. https://www.sciencedirect.com/science/article/pii/S1631070511001873?ref=pdf_down load&fr=RR-2&rr=83d82102ea9f06b0
3. http://grounddown.uchicago.edu/~whu/Courses/Ast321_17/Baryogen_Lecture.pdf
4. https://www.bbc.com/news/science-environment-52297058
5. https://arxiv.org/pdf/2105.01406.pdf
6. https://www.forbes.com/sites/startswithabang/2019/11/19/the-strong-cp-problem-is-the-most-underrated-puzzle-in-all-of-physics/?sh=45e0e7ab1ea7
7. https://cerncourier.com/a/cp-violation-past-present-and-future/
8. https://www.slac.stanford.edu/gen/meeting/ssi/1999/media/cohen.pdf
9. http://hyperphysics.phy-astr.gsu.edu/hbase/Particles/cronin.html
10. https://phys.org/news/2016-07-cp-violation-physics.html
11. https://www.symmetrymagazine.org/article/charge-parity-violation
12. http://hyperphysics.phy-astr.gsu.edu/hbase/Particles/kaon.html#c1
13. http://large.stanford.edu/courses/2008/ph204/coleman1/
14. Advances_in_Modern_Cosmology/
15. https://arxiv.org/pdf/1410.1100.pdf
16. https://arxiv.org/pdf/hep-ph/9603208.pdf
17. https://www.dunescience.org/

GLOSSARY

1. Meson: a particle containing the combination of a quark and an antiquark. 2) Pion: the lightest meson.
2. Eigenstates: If we apply a transformation to a vector A and we get a value of the same vector times a scalar, then that vector A is an eigenstate.
3. Collimator: a device for producing a parallel beam of rays/ radiation.
4. leptons: One of the two subgroups of fermions, the other being quarks, containing electrons, muons, tauons, muons, electron neutrinos, muon neutrinos and tao neutrinos.
5. Majorana particles: Particles that are their own antiparticle.
6. The PMNS matrix: In particle physics, the Pontecorvo–Maki–Nakagawa–Sakata matrix (PMNS matrix), lepton mixing matrix, or neutrino mixing matrix is a unitary mixing matrix which contains information on the mismatch of quantum states of neutrinos when they propagate freely and when they take part in weak interactions. It is a model of neutrino oscillation.
7. Quarks: These are elementary particles that constitute matter since they form protons and neutrons. Quarks are categorized as fermions, obeying Fermi-Dirac statistics, and they possess fractional electric charges.
8. Decay angle: The angle between certain momentum vectors associated with the decay products. In the paper, it refers to the angle between the direction of one of the decay products (e.g., a pion) and the direction of the parent kaon in the kaon's rest frame.