# Matters of Antimatter: Its Troubling History and Mystery

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**Abstract**

*It has become the new focus of countless science-fiction novels. It is at the center of debate for chemists and particle physicists all over the world. It has changed the way scientists view the universe. The surprising culprit: antimatter. Judging from its name, one may think it is merely the "mirror-image" of the matter we all know and see. However, it is this misconception that is the cause for all the uproar. Through simple observation, scientists can say with certainty that matter dominates over antimatter, but the reason why is unknown and quite troubling. Not only do matter and antimatter not act as "mirror-images" in the sense of a common house-hold mirror, but they display other asymmetrical behaviors as well. To the scientists who held the belief that nature is symmetrical, this is unfortunate news. The following paper will explain the differences between matter and antimatter, as well as map out the timeline from a supposed initial state of equilibrium between matter and antimatter to the asymmetry we observe today, discussing the possible routes taken in the meantime. Additionally, I will outline the types of symmetry and symmetry-breaking, relating them to the matter-antimatter asymmetry, discuss the importance of each, and explain the role that they play. Through such analysis I will ultimately reveal why scientists were so concerned with the asymmetry of antimatter, and whether or not these feelings could be justified.*

## Introduction

Antimatter is a relatively new topic in science, having only been found in the last eighty or so years, and only recently has it been studied more intensively. Unfortunately for the curious scientist, it appears that the more that is learned about antimatter, the bigger the mystery it becomes. Formerly, it was believed that matter and antimatter were similar, but different. What this means is that scientists believed it would have oppositely charged particles, such as protons and antiprotons, but would have the same physics behind it. If that were so, however, the universe as we know it would not exist. In fact, we probably would not exist, because when matter and antimatter meet, they annihilate each other, leaving behind two photons (Koczer**)**. Thus, if equal laws were behind matter and antimatter, the universe would have been created and destroyed in an instant. Today, scientists say with much assurance that the universe appears to consist entirely of matter, and so the asymmetry begins here. Such a lack of equality truly bothers scientists, and I will address the reasons why that is.

I will start by giving a brief factual background of antimatter, including its unique traits and its history from the early days of the universe up until today. Then, through examining the origin and types of symmetry, we can determine how it correlates to antimatter. By exploring and applying Occam's Razor to the debate as well, it will become clear why scientists choose the explanations that they do, and whether or not they are justified. By definition, Occam's Razor should not be a scientific law, but rather a rule of thumb, and I will argue that it should remain just that, despite the fact that some scientists grant it more worth. To unearth why antimatter and its asymmetry were such daunting discoveries, as well as to find the appropriate usages of Occam's Razor would not only help to paint a better picture of our universe, but perhaps prove useful in future scientific discoveries.

**Matter's Evil Twin**

The discovery of antimatter was speculative, as well as accidental, when scientist Paul Dirac stumbled upon it. Dirac was fiddling around with some mathematics, attempting to create a new equation to combine Albert Einstein's special theory of relativity and quantum mechanics. This new equation, now called the Dirac equation, was able to better explain more properties of the electron. It received much credit for correctly proving some of the known quantitative factors of the electron. In 1933, he would receive the Nobel Prize for this work, which he was hesitant to accept for fear of attracting attention to himself (Quinn and Nir 42). Before contemplating his award, however, Dirac was also reluctant to announce his discovery. Aside from being an introvert, Dirac put off his findings because he noticed something quite odd. In addition to the negative charge of the electron, the equation allowed for a positively charged particle. Being that only the proton was known for its +1 charge, it seemed the obvious choice. However, the mass did not match up. As Dirac and his colleagues tried to fix the equation to fit the proton, it was becoming clearer that something else was responsible for this "mistake." That something was the antielectron (Quinn and Nir 43-44). Dirac was cautious to announce this idea, and appeared skeptical himself, saying he still had "not yet worked out mathematically" some of the other minor factors he excluded (Quinn and Nir 44). Nonetheless, he had just opened the door to a new realm of particle physics that would only become more perplexing.

At the time of his discovery, it is doubtful Dirac knew how far his equation would take physicists. Today, we know that in addition to the antielectron, also called the positron, there are antiprotons, antineutrons, and other evil twins of elementary particles, such as mesons. More specifically, just as these matter-particles, known as hadrons, are made of quarks, their anti-partners are made of corresponding antiquarks. As expected, the antiproton has the same mass of a proton, but with a -1 charge, and made of two antiup quarks, and one antidown quark, just as the proton consists of two up quarks and one down (Gilman). The mesons are unique, however, in the way that they are made of a quark and an antiquark. Thus, the "anti-meson," consists of the corresponding counterparts of each and is just a meson in itself (Quinn and Nir 94). One may wonder if we already knew about protons, why not the antiprotons? The answer is because scientists had yet to detect their existence first-hand. In fact, it was not until recently that scientists were even able to create these antiparticles in a lab, the reason being that when a particle and its counter-particle meet, they "annihilate," and turn into two photons (Koczor). Thus, even when created in the lab, antimatter is very unstable and difficult to study. Nonetheless, the more important issue here is where all the antimatter went, and why everything appears to be made entirely of matter. Such an asymmetry has been plaguing scientists for many years. To truly understand this imbalance, however, we must first discuss exactly what symmetry is.

**Symmetry and Symmetry-Breaking**

Symmetry is an idea that has existed far longer than the idea of antimatter, and has many different variations. It started out as an idea to unify different elements and in general, it was defined as "invariance under a specified group of transformations," which allowed it to be applied more extensively (Brading and Castellani "The Concept of Symmetry"). Eventually, it came to represent such things as unity and harmony. This gave it a peaceful, aesthetic appeal, and the idea of symmetry soon became popular in the fields of science, mathematics, and philosophy (Brading and Castellani "The Concept of Symmetry"). Likewise, the later idea of symmetry-breaking was disfavored by scientists, and such was demonstrated by the famous anecdote of a donkey called Buridan's Ass. In short, given two bales of hay placed equidistant from a donkey on either side, the donkey will have no reason to choose one over the other, and thus will starve (Brading and Castellani "Symmetry Arguments"). While this may be a crude and unrealistic example, it is useful in discussing scientists' reasoning behind symmetry-breaking: if there is no reason for something to go in one direction over another, it should not do anything. However, before discussing symmetry-breaking, it is important to define symmetry. In essence, there are two main types closely related to antimatter: parity and charge conjugation (Brading and Castellani "Symmetry Principles").

Parity, often denoted P, is a type of symmetry most people are familiar with. It is the symmetry that we experience when looking in a mirror. In general, it is the reversal of left and right, where our mirror-image's left hand is actually our right (Brading and Castellani "Symmetry Principles"). The question scientists began asking is whether or not nature can distinguish between left and right, and whether it has preference of one over the other. As it turns out, the answer is yes. Of the four fundamental forces in nature, strong interactions, weak interactions, gravity, and electromagnetism, only the forces of weak interactions violate P-symmetry. Because the other three forces are easier to study and more abundant, the idea of symmetry violation in the fourth force was not given much thought (Ryder 154-155).

The discovery of P-violation took place in 1956 by C.S. Wu, T.D. Lee, and C.N. Yang, in an experiment involving the beta-decay of a cobalt neutron. Wu, Lee, and Yang placed the cobalt neutron in a magnetic field, and observed the direction of electron emission (Quinn and Nir 71). What they found was, when the direction of the magnetic field and nuclear spin were reversed, as in a mirror, the direction of the electron emission remained the same (Ryder 154-155). This was a clear indication of parity violation; rather than the direction of the electrons being determined by the direction of spin, it was determined by nature's preference of one direction over another. It was rumored that previous experiments by other scientists had found similar results, but they had never been published because, like Dirac's discovery, it was an odd result (Quinn and Nir 71). This beta-decay experiment was a major breakthrough because it was the first confirmed experiment which showed that nature can sometimes differentiate between left and right.

A second type of symmetry was introduced by Dirac, called Charge Conjugation or C-symmetry, and, rather than left and right, it transposes matter for antimatter (Brading and Castellani "Symmetry Principles"). In the same experiment responsible for proving violation of P-symmetry, C-symmetry was observed to be broken as well. In an antimatter world, positrons would replace the electrons. As a result, the currents in the wire producing the magnetic field are due to positrons, and thus the magnetic field points in the opposite direction, and so does the nuclear spin. Nonetheless, the emission of positrons occurred in the same direction as the emission of electrons in the matter-world. Not only could nature appear to distinguish and prefer one direction from another, but it apparently could discriminate matter from antimatter. Once again, charge conjugation symmetry is only broken in weak interactions, and not the other three fundamental forces (Ryder 155). As a last resort, scientists concluded that the multiplication of the two symmetries, CP-symmetry, would be conserved in all aspects of nature.

**CP-Symmetry – A Last Hope?**

After the shocking discovery of C- and P- symmetry, scientists turned to its multiplication as a last chance for conserving symmetry. In a gedanken experiment, German for "thought," it would make sense for the two symmetries combined to call for invariance under normal conditions (Quinn and Nir 67). Lewis H. Ryder provides the reader with a good thought experiment. If talking to an alien friend and trying to decide whether or not they lived in a world like ours or completely opposite, one would ask them to perform the beta-decay experiment. If their results were different from ours, then either their left and right are opposite ours, or they are made of antimatter. If, on the other hand, their results were the same, we could conclude that either they are matter-beings, with their left being our left, or they are made of antimatter *and* have different lefts and rights. In this particular gedanken, the idea of CP invariance during C- or P-violation seems to make sense. As long as both are violated, CP symmetry should still hold (Ryder 156). However, the scientists' relief was short-lived.

In 1968, Val Fitch, James Christenson, Rene Turlay and James Cronin performed an experiment that produced unexpected results that would later lead to their Nobel Prize (Quinn and Nir 75). In an experiment with neutral kaons, or K-mesons, it turned out that CP invariance did not hold for particles and their antiparticles. In short, the experiment focused on the decay of two different K-mesons, one with a longer half-life, $K_L$, and one with a shorter half-life, $K_S$. Through complicated mathematics and observation, it was found that the $K_L$ meson violated CP-symmetry. Bertram Schwarzchild, author of "At Last We Have an Undisputed Observation of `Direct' CP Violation in Kaon Decay," says that the only direct evidence of CP-violation was that of neutral kaon decay and the fact that the world is dominated by matter. Their relationship is tentative (Schwarzchild 17-19). Despite the still-unknown foundations for CP-violation, the important point is that it exists, and is most likely responsible for the asymmetry of antimatter.

**In the Beginning…**

The Big Bang Theory is the most widely-known, widely-accepted theory when it comes to describing the creation of the universe. While this theory still faces scrutiny by some, scientists believe they have accurately hypothesized the conditions for the very beginning. In general, extreme heat, density, and rapid expansion dominated the first few seconds (Quinn and Nir 3-4). At such a point, most particle physicists argue that it would only make sense that matter, antimatter, and photons existed in thermodynamic equilibrium. In intense heat conditions, photons are able to collide to form an antimatter particle and a matter particle. At the same time, annihilation was happening, turning matter and antimatter into photons, thus establishing equilibrium. Once the universe began to cool down, however, photons were no longer able to produce particles and antiparticles, and so only annihilation could occur. Since matter and antimatter always annihilates despite temperature, and because it supposedly existed in equilibrium, it would make sense that the equal matter and antimatter annihilated completely (Quinn and Nir 63). Clearly, we now live in a matter-ruled universe. Something must have happened to cause an asymmetry in such a small time frame, and this particular something, called baryogenesis, is what worries scientists.

Within $10^{-6}$ seconds of the birth of our universe, it had already cooled down too much to produce baryons (protons and neutrons) and antibaryons from photons. If equilibrium had been previously established, the universe would have been instantly annihilated (Quinn and Nir 35). Clearly, this did not happen. While most scientists argue C- and CP-violation is the cause for our being, it is still unclear exactly what occurred during that very first second. A second theory calls for an initial imbalance of matter and antimatter, however, this theory is quickly discarded by most scientists. It probably bothers them because most of their estimates of the Big Bang theory do not require them to know exact initial conditions. If initial conditions do play a role, then other, already-accepted ideas surrounding the Big Bang must be thrown away too (Quinn and Nir 10). A final theory, which most scientists regard as science-fiction, is the existence of antimatter galaxies, far away from our matter galaxies. While the amount of annihilation and gamma-ray production that would have to occur at its borders cannot be accounted for, this theory cannot be totally ruled out, as there is still more universe to be looked at (Gilman). Nonetheless it is unlikely and it seems C- and CP-violation is something scientists had to learn to cope with.

**Simple Matters**

Now that the types of symmetries and symmetry-breakings have been discussed in light of antimatter and its history in the universe, I can begin to explain why symmetry-breaking is a daunting topic for scientists, using something called Occam's Razor. While Occam's Razor is not really a law, but rather a general rule of thumb, it is often applied in many fields, from science to economics, and has earned numerous definitions over its long history, each with slight nuances (Baker "Introduction"). To give a better definition of the Razor, it is often first divided into two types: parsimony and syntactic simplicity. Parsimony refers to the complexity of the idea or theory with regards to an observation, while syntactic simplicity has been synonymous with elegance and conciseness (Popper 142, 145). Together, the definition can be summed up in the following way: All other factors being equal, the simplest idea is often favored by scientists to explain a particular phenomenon. John Earman even quotes physicist Steven Weinburg as saying "Our job as physicists is to see things simply, to understand a great many complicated phenomena in a unified way, in terms of a few simple principles" (1229). It can be said, then, that Weinburg appears to subscribe to the syntactic simplicity. Similarly, Isaac Newton, a big proponent of Occam's Razor, deemed it Rule I in his "Rules of Reasoning in Philosophy," taken from ***Principia Mathematica*****. He writes, "**We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances" (Baker "Introduction"). Here, Newton is defining the Principle of Parsimony, explaining that as long as a theory accurately matches a repeated observation, complications are unnecessary. This directly applies to antimatter, and how so will be discussed in a moment. For now, it becomes a question of why people favor the Razor, and whether or not it is rightfully so.

The first justification for the use of Occam's Razor has its roots in theology. Many theologists argued that God had created a complete and simple world. For example, light took the shortest, and therefore simplest, path when traveling (Baker "*A Priori* Justifications of Simplicity"). Thomas Aquinas, an Italian Catholic priest from the medieval times, furthers this idea by saying, "If a thing can be done adequately by means of one, it is superfluous to do it by means of several; for we observe that nature does not employ two instruments where one suffices" (Baker "Introduction"). His statement supports the idea that simple is better, where other factors are equal. Baker furthers the theological justification, explaining that theologians and scientists alike believed God created a simpler and therefore more beautiful world. While people often attempt to differentiate between science and religion, scientists such as Isaac Newton and Johannes Kepler, shared this view (Baker "*A Priori* Justifications of Simplicity"). Religious or not, this theological perspective demonstrated the high value given to aesthetics, and allowed for the gradual change into more developed, scientific justifications for Occam's Razor.

A method for rationalizing the Razor can be seen with the idea of probability. A simpler hypothesis would be more likely to be true, given that they have fewer details to be proven true. Philosopher Karl Popper takes it even further. To define what "simpler" means, he explains that it is the "degree of universality" that determines it, because a more universal one, or one that applies to more results, can take the place of less universal ones (Popper 127). Then he writes that the simpler a hypothesis is, the easier it is to test. Moreover, the easier it is to test a particular claim, the more easily falsifiable it is. In short, simplicity implies testability, which then implies falsifiability, and falsifiability is an important criterion for scientific theories. In this sense, Popper is arguing something other than aesthetics to defend Occam's Razor, with something more grounded.

While it may be true that beauty is in the eyes of the beholder, scientists can usually concur with which theory is "beautiful." To start, Andre Kukla, author of *Methods of Theoretical Psychology*, uses parts from Paul Dirac's own works, and writes, "Indeed, many scientists…have suggested that their theoretical simplifications were motivated largely by the desire to beautify existing theories." However, Kukla then takes on both sides of this debate. He refers to such scientists as "fanatical classicists," due to their influence of traditional ideas, and jokes by asking where all the revolutionary "romantic theorists" went (144). However, Kukla goes on to explain the rationale as to what makes simplicity more beautiful. He says that simplicity is often preferred because it denotes two ideas: truth and utility. Concerning truth, Kukla quickly mentions the classic relationship between truth and beauty, remarking that one is embedded in the other, but then goes on to give a more logical approach (Kukla 144-145). As far as utility, he claims that the easier it is to use a particular theory, the more favored it is. He then brings Isaac Newton's theories of motion into play. Kukla believes that even though scientists are aware that Newton's theories do not paint the full picture, they still use them for simple calculations when they know the answer will be the same (144). Now we have a paradox. To have utility might mean to throw away the idea of truth, which in this case, would be the true theories of motion. Conversely, however, when it comes to ease of use, the methods themselves may not be true, but truth is restored, so long as the end result is correct. Depending on one's view of truth depends on whether or not truth is maintained.

**So What's the (Anti)Matter?**

Now that I have outlined the definitions and justifications behind Occam's Razor, it is important to mention how it applies to symmetry, and ultimately, the matter/antimatter debate. Symmetry, in all aspects previously described, is one facet of simplicity. Just as it was argued by theologists that simplicity was a rule of nature, it was formerly believed that symmetry was also embedded in nature. And, as scientists say simplistic ideas have a greater chance of occurring, many could argue, in the case of the Buridan's ass, that symmetry is more likely to occur than not. After all, symmetry was held in most aspects of nature. And lastly, just as symmetry represents beauty and unity, the "classical scientists" that Kukla mentions say the same about simplicity. From this train of logic, we can conclude that symmetry and simplicity can and usually do go hand-in-hand. Thus, it would make sense that the theory which holds symmetry should also be the one favored by Occam's Razor.

Clearly, at some point in the early universe, matter gained a slight advantage over antimatter, and created the universe we observe today. Thus, it is safe to conclude that symmetry was broken, just as it had been seen to be broken when it came to parity, charge conjugate, and the multiplication of the two. However, this conclusion did not come easily for scientists at first. Why else would Dirac be so cautious to announce his findings of the antielectron, and why else would previous results of parity-violating experiments be kept under wraps? Clearly, the whole idea of antimatter and its asymmetrical qualities was a new and perhaps scary idea. However, new ideas and theories are created all of the time, and usually they are not so hidden. Something was different about the antimatter and symmetry-breaking discoveries. That something could certainly be attributed to Occam's Razor.

Up until recently, antiparticles had not been directly observed firsthand, due to the fact that their lifespan is incredibly short, and the creation of it calls for extreme conditions. As such, because it had never been seen, there was no reason to believe it was there until Dirac's equation. Just as Newton had elegantly put it in his "Rules of Reasoning in Philosophy," we should not assume any more than what we see to explain phenomena around us. Such assumptions would only complicate theories on the universe. This is the essence of parsimony. As such, when Dirac and other scientists proved beyond reasonable doubt that antimatter existed, they had to take one giant step away from Occam's Razor. Such a step must have been difficult to make, otherwise, it would not have taken so much hesitation. Likewise, bringing symmetry back into the picture, the experimenters before Wu, Lee, and Yang must have had even more trouble taking that step, because they never formally reported their findings. Just as I mentioned that symmetry correlates to simplicity, symmetry-breaking must therefore stray from simplistic ideas as well.

While there are several justifications behind Occam's Razor, all of which are logical, hard scientific evidence should weigh more on the scientists' minds. As far as the theological/naturalistic rationale, just as the idea of symmetry being a law of nature was discarded, so should be the idea of simplicity being a law of nature. In many aspects, such as three of the four fundamental forces, symmetry did hold. But, for that last force, weak interactions, symmetry-breaking was unavoidable. So, while it was a good idea for the most part, symmetry cannot be considered a law of nature. Likewise, simplicity may often work and be intuitively justified, but it is not a law, and should not be upheld as if it were. As with all theories, once it no longer applies, the theory is abandoned. So then, as symmetry being rooted in nature was reluctantly forsaken, so should the idea that simplicity is always the best choice when all other factors are equal.

Karl Popper's view, on the other hand, makes some valid points that have their roots in something more than just pure intuition. His idea of using testability and thus probability demonstrate a greater knowledge, and most importantly, it leaves room for deviance. He never states that simpler explanations should be preferred, but just that they often are preferred due to testability, and thus have a greater chance of being correct. In many cases, both statistically and intuitively, this seems logical, and usually it works. When it comes to deviance, antimatter and asymmetry can be considered the exception to Popper's rule. However, overall, I think it is safe to say his rule can suffice due to its rationality and room for errors, unlike Occam's Razor itself.

Lastly, the view held by Kukla enforces aesthetics as being the culprit for capturing scientists' imaginations. I strongly believe that it is true, and that aesthetic appeal plays a major role in scientific explanation. After all, even Dirac himself confessed scientists' desire to beautify theories. He uses the term "classical" to describe such scientists who favor this, and rightfully so, as symmetry had been used to represent beauty since the days of Plato (Brading and Castellani "The Concept of Symmetry"). While classical ideas should be given credit for setting foundations, when other, better ideas come about, tradition should be set aside. On the other hand, going back to his reference to Newton, I can agree that utility is important, and that it does make sense to continue using his laws of motion for some calculations. However, this brings up two important issues: where do we deem it appropriate to use simple methods over complicated ones, and how do we mend the paradox on truth.

Concerning the first issue, the demarcation between when to use simple equations verses complex equations is blurry, and there probably is no definitive line drawn. The only sensible guide would be to use the complex theory, assuming it to be correct, when in doubt. This holds true in the case of Newton, in that his simpler theories predict the physics we observe on Earth, but not on a larger scale. Thus, when uncertain, it may be wiser to use the more complex theory. This brings us to the second issue of truth. Kukla presses that beauty is in line with truth. However, by using the example of Newton's theories, where should the truth lay: in the method, or in the result? It seems as though Kukla favors the latter version of truth, but then one may ask why should we then bother finding new and better methods if the result is the same in many instances? Again, I admit that Newton's methods are easier, but one must be careful in the ways that they are used. In the case of Newton's theories, his simplistic ideas, while useful on Earth, have their limitations. All in all, depending on one's particular definition of truth, as well as the situation, simple is not always the best choice in the absence of evidence.

All things considered, it is clear that simplicity due to Occam's Razor is still upheld by scientists. While it originated as just a guideline and not a defined law of science, it became clear that some scientists still continue to depend on it and accept it as fact, and are wary of results that do not follow it. I can agree that it is often logical to use Occam's Razor, but scientists should not be too concerned when symmetry, or simplicity, fails to the point that true science is discarded because of an odd result. If there are two results, one of which being the simpler, and there is no evidence of one being better than the other, then it is perfectly reasonable for scientists to apply Occam's Razor. However, having too much faith in it, or putting too much emphasis on "beautifying theories" could have serious consequences. After all, had Dirac been too skeptical of himself, or had Wu, Lee, and Yang also never published their results, scientists today probably would not be where they are with antimatter, and possibly other aspects of science as well. In a time with such scientific advances like antimatter and large hadron colliders, it is a mystery that heavily intuitive, blurry ideas like aesthetics should have such a role in something as grounded as scientific theories. Overall, it was a hard lesson for Dirac and the other scientists to learn, but nonetheless, a valuable one that could serve as an example for all future discoveries.

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