Where did the antimatter go?

Is baryogenesis a correct explanation for the fact that there is only matter in the universe?

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Introduction

On September 29, 2023, Nanna Vium wrote the following article in ‘Wetenschap in Beeld’: ‘*After decades of head-scratching: Major discovery about antimatter*’. [1]
The introduction reads as follows:

“*As we all know, the universe originated 13.8 billion years ago from a single point in nothingness through a massive burst of energy known today as the big bang.*
The extremely dense and hot point began to expand and cool down, causing some of the energy to concentrate into particles.
According to modern physical theories, this should have created an equal number of matter particles, each with a sort of twin with opposite electric charge: antimatter.
In the second after their formation, matter and antimatter particles should have annihilated each other, leaving behind an empty, radiation-filled space with no matter, no gases, no galaxies, and no planets.
The problem is that we live in a universe full of matter and very little antimatter.
So the question is: what happened to the other half of the universe, the antimatter particles? And why didn’t matter and antimatter annihilate each other completely before we even existed? Something doesn't add up!
The disappearance of antimatter is one of the biggest mysteries and most open questions in physics.
Despite many successes with the Standard Model of particle physics, no one has yet been able to explain where the antimatter particles went. Something must be going on with antimatter, because nature somehow chose for the matter twin to survive alone.”

Several theoretical mechanisms have been proposed to explain this discrepancy. [2]
The two main interpretations are:
either the universe began with a small preference for matter,
or the universe was originally perfectly symmetric, but a series of phenomena contributed to a slight imbalance in favor of matter.
The second view gained more traction: **baryogenesis**.
However, there is still no clear experimental evidence that definitively confirms either mechanism.

A team of physicists at CERN, the European particle physics institute, made an important discovery that may one day bring us closer to the answer, the article says.

What was the experiment?
Jeffrey Hangst and his colleagues created antihydrogen and set up a vertical experiment to demonstrate that antihydrogen responds to gravity just like hydrogen: it falls downward and not upward.
Though the result still carries a 20% uncertainty margin, the team is working to reduce that to 0.1%, to be absolutely sure that both hydrogen and antihydrogen experience the exact same gravitational acceleration.

That’s where the article ends.

What is baryogenesis?

According to Wikipedia:
In cosmology, baryogenesis is the general term for **hypothetical physical processes that caused an asymmetry between baryons and antibaryons** in the very early universe, resulting in the matter that now makes up the visible universe.

A baryon (Greek: βαρύς, barys, meaning "heavy") is a subatomic particle made up of an odd number of quarks (at least three). Common examples include the proton and neutron.
The baryon number is calculated as the number of baryons minus the number of antibaryons.
The baryon number B of the universe is estimated at around 10^{78}.

One of the most striking problems in modern physics is the dominance of matter (baryons) over antimatter (antibaryons) in the universe. [2]
The universe appears to have a positive baryon number density that is not zero. Given that the particles in question are assumed to have been created under the same physics we observe today, it would be expected that the total baryon number is zero, that is, matter and antimatter were created in equal amounts.
Researchers attempt to explain this discrepancy by identifying conditions that would break symmetry and favor the creation of regular matter over antimatter. This imbalance must have been extremely small, on the order of 1 in every 1.63 billion ($\approx 2\times10^9$) particles, a fraction of a second after the big bang. After most matter and antimatter annihilated each other, only baryonic matter remained in today's universe, along with a much larger number of bosons. Bosons are their own antiparticles.

However, experiments reported in 2010 at Fermilab suggested that this imbalance may be much larger than previously thought. These experiments involved a series of particle collisions and found that the amount of matter produced was about 1% greater than that of antimatter. The reason for this difference remains unknown.

Most ordinary matter in the universe exists in atomic nuclei, made of neutrons and protons. These nucleons consist of smaller particles called quarks. According to Dirac's 1928 equation, antimatter counterparts exist for each type of quark, and these have all been experimentally verified.

Theories about the early moments of the universe predict nearly equal amounts of quarks and antiquarks. When the universe expanded and cooled to a critical temperature of about 2×10^{12} K, quarks and antiquarks combined into **matter and antimatter and annihilated each other—except for a slight asymmetry of roughly one part in five billion, which allowed the matter we see today to remain.**

Free, isolated quarks and antiquarks have never been observed in experiments; they always appear bound in groups of three (baryons) or in quark-antiquark pairs (mesons).
Likewise, there is no experimental evidence that significant concentrations of antimatter exist in the observable universe.

The conditions of Sacharov [3] [4] [5]

In 1967, Andrei Sacharov published an article in the *'Journal of Experimental and Theoretical Physics'* on the topic of

baryogenesis. In it, he argued that in certain situations, a violation of symmetry could occur.
He specifically referred to what is known as CP-symmetry, the symmetry in both charge and parity transformation. C stands for charge, P stands for parity (mirror image).

It was long believed that combining these two individual symmetries would yield a conserved symmetry: CP-symmetry. However, violations of this symmetry have also been observed in the weak interaction, as demonstrated by earlier experiments.

But these violations alone do not lead to a surplus of baryons over antibaryons. In other words, they cannot explain the observed imbalance between matter and antimatter in the universe.

Sacharov therefore concluded that more was needed. He proposed three conditions that must be met during the big bang in order for baryogenesis to occur. That is, for matter and antimatter to be created at different rates:

1. the universe must be out of thermal equilibrium;
2. there must be violations of both C- and CP-symmetry;
3. there must be interactions that violate baryon number (B) conservation.

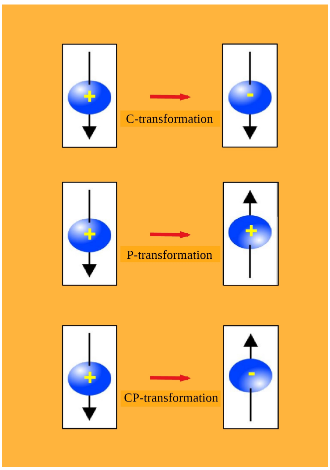
The first condition is easily met because we live in a universe that is cooling and expanding. It is not in equilibrium.

C-symmetry stands for charge conjugation symmetry (charge conjugation is a transformation that exchanges all particles with their corresponding antiparticles, thus changing the sign of all charges).

C-symmetry simply means that the laws of physics must apply equally to antimatter and matter (see above about the antihydrogen experiment).
The weak force continually breaks C-symmetry. This is because neutrinos and antineutrinos each have only one type of spin (neutrinos' spin is always clockwise, antineutrinos' spin is counterclockwise).

CP-symmetry is the combination of C-symmetry and P-symmetry. Parity in the context of particles can represent spin, so a particle with clockwise rotation, for example, would rotate counterclockwise.

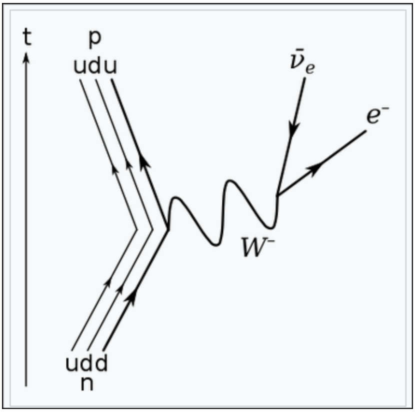
The weak force has processes that violate the CP-transformation and thus CP-symmetry. However, there are not enough CP-violating interactions to explain the difference in the amount of matter and antimatter.



Source: Rik Gielen

C-, P- en CP-transformation

The final condition regarding the violation of the baryon number is also problematic. A baryon is a particle composed of three quarks. Generally, you cannot destroy baryons; you can only change them.



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Beta decay

For example, in beta decay, a neutron can change into a proton and vice versa. Beta decay results in a CP-violation! To meet the third Sacharov condition, we need a process that can transform one baryon into two. We have never observed this.

Apparently, there is an underlying rule in the interaction between particles that ensures that matter and antimatter are not exactly opposites. Therefore, scientists have chosen the practical approach to understanding the disturbed equilibrium: experimenting until the differences between matter and antimatter become apparent (see article above).

The question therefore remains: what causes the asymmetry between matter and antimatter? There are several speculative theories.

Some speculative theories [4] [5]

One theory stems from Richard Feynman's theory that antimatter is mathematically equivalent to ordinary matter moving backward in time. So perhaps antimatter began traveling backward in time during the Big Bang and never encountered matter. Perhaps the universe ‘collided’ in two opposite directions in time.
The problem with this hypothesis is that the antimatter we observe is all moving forward in time, not backward.

Some suggest that mirror antimatter galaxies may exist in distant regions of the universe. However, if this were the case, we would expect high-energy gamma rays from the boundary regions where matter objects encounter antimatter objects. Such phenomena are not observed.
One way we could find out is by studying the *gravitational wave background*, but our instruments are not yet powerful enough to detect this.

Professor Sijbrand de Jong of Radboud University Nijmegen once said: "A highly speculative and unrealistic explanation I once came up with stems from the observation that almost all galaxies have a very massive black hole at their center. *The antimatter could be concentrated in the black hole, while the matter orbits it as a galaxy.* The black hole's horizon would then form a natural barrier that keeps matter and antimatter separated. However, I have no idea how that situation could have arisen."

The brilliant physicist Stephen Hawking [6] gave several lectures on black holes. He expressed his conviction that it should be possible *to travel through a black hole to a parallel universe*. He added, however, that it would have to be a ‘very large, actively spinning black hole’. Incidentally, according to the scientist, anyone embarking on such a spatiotemporal journey shouldn't expect a return ticket home.
He also said: "The message of this lecture was that black holes aren't as black as people imagine. They're not the eternal prisons they're believed to be," Hawking said during a lecture. "Things can escape from a black hole and possibly even *emerge in another universe*."

There have been many recent theoretical developments to address this asymmetry between matter and antimatter. Crucially, many new physics models that generate the baryon asymmetry have a wide range of implications for many areas of theoretical and experimental particle physics.

The Standard Model of particle physics cannot explain the observed baryon asymmetry of the universe. This finding is a clear sign for a new physics that goes beyond the Standard Model.

> The current Standard Model of particle physics was developed through laboratory experiments and brilliant theoretical ideas. This model should be applicable to the universe as a whole. It should enable the calculation of all cosmological parameters, such as the baryon number of the universe.
>
> The inability of the current Standard Model to fully account for the observed universe (dark matter, dark energy, inflation, baryogenesis) indicates that the current Standard Model cannot be the definitive Standard Model of particle physics.
> Cosmological considerations can point to directions for physics that go beyond the current Standard Model. Baryon asymmetry is one example.

Source: Rik Gielen

About the current standard model of particle physics

The universe and symmetry [7]

Until 1967, the laws of physics always required symmetry for the creation and destruction of particles, that is, equilibrium in the number of particles and antiparticles,. But then, that year, Sacharov published his article. In it, he argued that symmetry violations can occur in certain situations.
And since then, scientists have been seriously engaged in explaining many very complex phenomena using symmetry breaking (for example: electroweak symmetry breaking, which is responsible for giving mass to elementary particles such as the W and Z bosons and the Higgs boson).

Yet the universe is very fond of symmetry.
Symmetry is a common feature and occurs at various levels.

1. Cosmic symmetry: in the cosmos, there are many examples of symmetry, such as the even distribution of galaxies, the symmetrical shape of spiral galaxies, and the symmetry of planetary and lunar surfaces.

2. Molecular symmetry: in the world of molecules, symmetry is an important concept; molecules can have different types of symmetry, such as rotational symmetry, mirror symmetry, and inversion symmetry.

3. Symmetry in nature: in nature, we also find many symmetrical patterns, such as the symmetry in flowers, leaves, snowflakes, and crystals.

In short, symmetry is a widespread concept in the universe and can be observed at many levels.

It therefore seems logical to me that the universe would have adhered to the principle of symmetry during its own creation.

Proposed solution: an anti-universe in its own space

How then should we view the asymmetry between matter and antimatter? In what direction should we think to come up with a better and more logical explanation than baryogenesis?

Let's consider the speculative theories mentioned above.

What Richard Feynman is saying essentially implies that ***time*** *must keep matter and antimatter apart* in our universe.

The second theory, that of mirror antimatter systems, essentially states that ***space*** *must keep matter and antimatter apart* in our universe.

Neither view offers a solution: the annihilation of matter and antimatter may have already occurred or will certainly occur someday.

Professor Sijbrand de Jong's idea seems appealing to me!

Why not extend this reasoning logically and also try to maintain symmetry, while taking Stephen Hawking's statements into account?

Let's place matter and antimatter in different spaces: *matter in our three-dimensional space, our universe, and antimatter in another three-dimensional space, an anti-universe*.

What should we imagine of an **anti-universe**?

That's a universe next to our own. Our universe has three spatial dimensions (1, 2, 3). The anti-universe has its own three spatial dimensions (4, 5, 6). This way, annihilation is impossible, and the symmetry of the universe is also beautifully preserved.

We can go one step further. Every galaxy in our universe has a symmetrical counterpart in the anti-universe, an anti-galaxy. Nice, but what about the supermassive black holes in both galaxies?

These form just *one supermassive black hole, and it must be located in a seventh dimension*, so between our three dimensions and the three dimensions of the anti-universe. Makes sense, right?

To see how this works, we can consider universes with only two spatial dimensions (see the following figure).

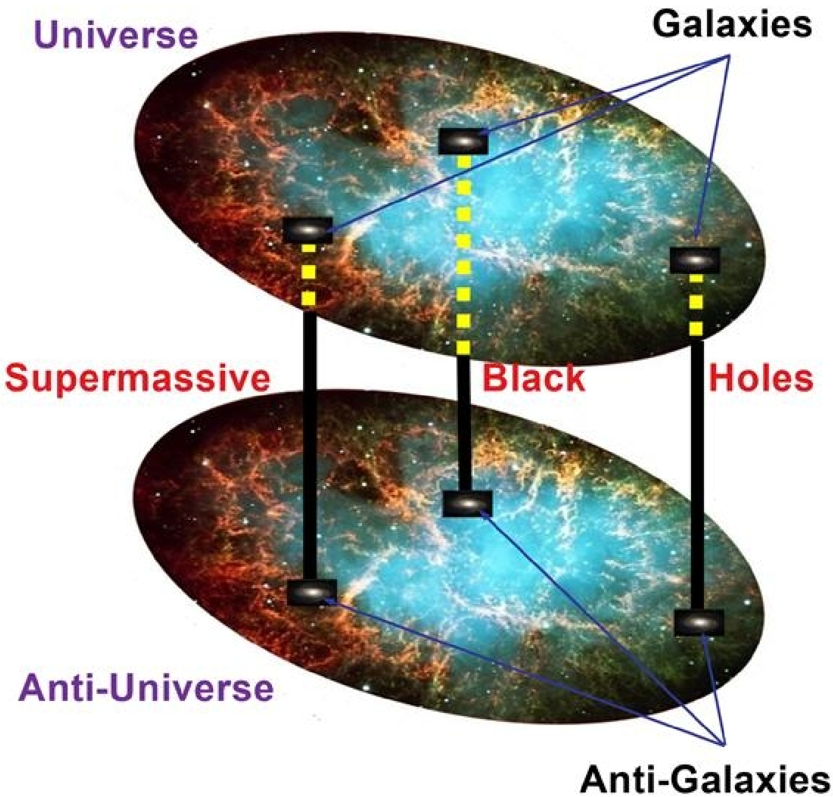
Imagine our universe as a flat plane containing billions of galaxies, which are therefore also flat. Each galaxy has a supermassive black hole at its center, bounded by its event horizon, which in this case is a circle.

Imagine the anti-universe at a distance above our universe, also a flat plane and also with its billions of anti-galaxies. Each anti-galaxy has a supermassive black hole at its center, bounded by its own event horizon.

Using black tubes, we can connect the symmetrically opposite supermassive black holes into a single entity, each in an extra dimension. In this way, the black tubes have become ***supermassive black wormholes***, connecting our universe and the anti-universe via the centers of the respective galaxies.

Now, if we move from these two-dimensional universes to three-dimensional ones, we can begin to understand it.

Voilà, the antimatter is found, and the symmetry is preserved!



Source: Rik Gielen

Universe and Anti-Universe connected by Supermassive Black Wormholes

We should also add that neutron stars and stellar black holes (the remnants of supernova explosions) do not cross from the universe to the anti-universe, or vice versa. Only supermassive black holes merge to form supermassive black wormholes.

In search of extra spatial dimensions

The view described here could become a sound theory if we receive more and more assertions and evidence from scientists who are making significant efforts in the field of extra spatial dimensions.

Several scientists have already made a start.

* “If there are extra dimensions in the universe, [8] gravitational waves could travel along any dimension, even the extra dimensions,” says *Gustavo Lucena Gómez of the Max Planck Institute for Gravitational Physics in Potsdam, Germany* Lucena Gómez and his colleague *David Andriot* began calculating *how potential extra dimensions would affect the gravitational waves we observe*. They found two remarkable effects: extra waves at high frequencies and a change in how gravitational waves stretch space.

As gravitational waves propagate through a small extra dimension, the team discovered, they should generate a "tower" of extra gravitational waves at high frequencies following a regular distribution. However, current observatories cannot detect such high frequencies, and most planned observatories also focus on lower frequencies. So, while these extra waves could be everywhere, they will be difficult to detect.

The second effect of extra dimensions may be more observable, as it alters the "normal" gravitational waves we observe rather than adding an extra signal. "If there are extra dimensions in our universe, this would stretch or contract spacetime differently than standard gravitational waves," says Lucena Gómez.
As gravitational waves ripple through the universe, they stretch and compress space in a very specific way. It's like pulling on a rubber band: the ellipse formed by the band lengthens in one direction and shortens in the other, then returns to its original shape when you let go. *But extra dimensions add another way for gravitational waves to change the shape of space, a so-called breathing mode*.
Just like your lungs do when you breathe, space expands and contracts as gravitational waves pass through, in addition to stretching and compressing. "With more detectors, we'll be able to see if this breathing mode is happening," says Lucena Gómez.

* "Extra dimensions have long been discussed from various perspectives," says *Emilian Dudas of the École Polytechnique in France*. "Gravitational waves could give a new twist to the search for extra dimensions."

* According to a controversial theory by *Dejan Stojkovic* [9] *(Department of Physics, University at Buffalo)*, our universe resembled a line more than space as we know it shortly after the Big Bang. Stojkovic and his colleague Jonas Mureika have now devised a test to prove whether their theory is correct: the absence of gravitational waves from the early universe. And there's more. *Perhaps large parts of the universe have already become four-*

dimensional. Could this explain those strange cosmic voids between galaxies and the accelerated expansion of the universe?

Stojkovic's theory essentially states that the universe was one-dimensional immediately after the Big Bang. As the universe cooled further, the second and eventually the third dimensions emerged. *The assumption of an era of extremely rapid inflation, currently the dominant paradigm in cosmology, is therefore no longer necessary*, Stojkovic argues. What happened was simply the emergence of the second and third dimension, respectively, causing the number of possibilities for motion (which we perceive as space) to explode.

The most hallucinatory consequence of Stojkovic's theory is the emergence of an extra dimension in the here and now. About ten years ago, a discovery was made that significantly disrupted conventional cosmology. The universe is expanding at an ever-increasing rate. Cosmological models assume that so-called dark energy is responsible for this. Nonsense, Stojkovic argues. *Increasingly larger parts of the universe are transitioning to the fourth dimension, which we perceive as expansion.*

* "Extra spatial dimensions seem at first [10]
like a wild and crazy idea, but there are strong reasons to believe that there really are extra dimensions of space", says *Lisa Randall, a professor of physics at Harvard University.*

Randall argues that the six curled dimensions considered in string theory can be infinitely large, provided space has a warped geometry. In fact, we could live *in a three-dimensional region of a higher-dimensional space*. Randall calls these regions of space branes. Just as a bead on a string can only move along one dimension, a brane can restrict our motion to three dimensions, although other dimensions also exist.

With branes, Randall discovered a way to explain how extra dimensions can be hidden and infinitely large. Because the mathematics behind her theory works, theoretical physicists have paid considerable attention to her research.

* *Milenna van Dijk, Institute for Theoretical Physics, University of Amsterdam*, writes in her PhD thesis ‘Warpted Extra Dimensions’ supervised by Professor Jan de Boer: "Perhaps we live in more than four dimensions. Models that assume extra dimensions include the Randall-Sundrum models I and II, with a warped extra dimension and two branes and one brane respectively. The one-brane model (RSII model) yields an infinite extra dimension, while the two-brane model (RSI model) provides a solution to the hierarchy problem. For these models, the background metric is determined, and the consequences for gravity in four dimensions are worked out. The two-brane model may soon be tested at the LHC." [11]

* The reason to consider extra dimensions is that they could offer a solution to the so-called ‘hierarchy problem’, simply put, the mystery of why gravity is so weak compared to the other fundamental forces. Even though gravity doesn't feel weak, especially when you're cycling up a mountain, its influence is relatively small when you consider that a small magnet can lift a paperclip despite the entire earth pulling on it.
Gravity could be so weak because *it's the only force that can spread across extra dimensions*. This would, simply put, leave less gravity for the three dimensions we know.

* In summary, various experimental techniques are being developed to investigate the existence of extra dimensions. These techniques range from high-energy particle colliders to precise measurements of gravity to astronomical observations of gravitational waves. Although the search for extra dimensions is still going on, the development of these experimental techniques is crucial for advancing our understanding of the fundamental nature of the universe.

Conclusion

In the first part of this paper we have shown in detail that it is **highly unlikely that baryogenesis is a valid explanation for the asymmetry between matter and antimatter.**

In the second part, we attempted to propose **a solution that preserved symmetry in the universe.**
The result: **an anti-universe in its own three spatial dimensions.**
With the added bonus that we can simply forget about baryogenesis.

Once the research into extra spatial dimensions yields tangible results, we will be strengthened by this and can continue to build a beautiful and logical theory of a *twin universe with the matter in our universe and the antimatter in the anti-universe*.

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