Antimatter: Separating Fact from Fiction

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Abstract

Antimatter is a fundamental aspect of the Standard Model of particle physics, recognised as the most accurate framework in the field. This dissertation delves into the theoretical foundations, historical developments and ongoing experiments in the field to demystify antimatter by separating factual scientific knowledge from fictional portrayals.

We discuss how scientific theories can be applied to a fictional example of the antimatter fuel on board the *USS Enterprise*, from the popular *Star Trek* franchise and find that, although it has aspects rooted in real physics, there is still a significant gap between its concepts and current scientific feasibility.

Contents

1 Introduction

In science fiction, antimatter of often portrayed as an exotic substance with explosive characteristics. In reality, antimatter is no more exotic than matter. The concept of antimatter dates back to Arthur Schuster's letter to *Nature* in 1898, where he hypothesised antiatoms that would yield energy if they combined with atoms of matter [1], and was then further established by scientists like Paul Dirac who made a direct prediction of the antiatom for the electron (the positron) which was later experimentally proven.

At the heart of the study of matter and antimatter lie the fundamental constituents known as quarks and leptons, as described by the Standard Model of particle physics which details the basic particles and forces of the universe, excluding gravity. Quarks are the building blocks of hadrons, which split into families containing three quarks (baryons such as protons and neutrons) and two quarks (mesons such as pions and kaons), while antiquarks are that of antihadrons. Leptons are elementary particles that include the familiar electron along with the muon, the tau and their respective neutrinos - all with antiparticle correspondents [2]. The elementary particles are show in Figure 1.

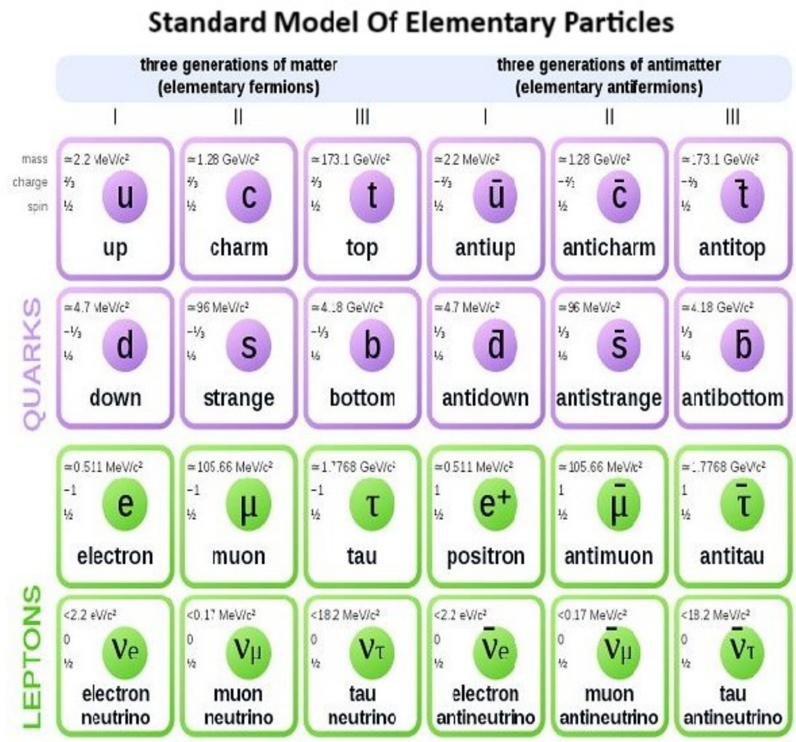

Figure 1: Standard model of elementary particles [3]

The distinction between matter and antimatter rests on the inversion of specific properties of particles, such as electric charge, baryon number and lepton number. Particles and antiparticles possess opposite charge, for example a proton has a charge of $+e$ while an antiproton has $-e$. Baryons and leptons have, respectively, a baryon number and lepton number of $+1$, while antibaryons and antileptons have a baryon number and lepton number of -1. Flavour quantum numbers, specific to types of quarks, are also reversed between corresponding matter and antimatter partners, shown in Table 1.

Quark	Charge (e)	Baryon Number	Strangeness	Charmness	Bottomness	Topness
Up	+2/3	1/3	0	0	0	0
Down	-1/3	1/3	0	0	0	0
Charm	+2/3	1/3	0	1	0	0
Strange	-1/3	1/3	-1	0	0	0
Top	+2/3	1/3	0	0	0	1
Bottom	-1/3	1/3	0	0	-1	0

Table 1: Flavour quantum numbers of quarks. Note: For antiquarks, these values are inverted.

This balance of properties between matter and antimatter leads to a profound consequence upon interaction: annihilation. When a particle interacts with its antiparticle counterpart, they can annihilate each other, converting their combined mass into energy, often in the form of energetic photons. This process is governed by Einsteins $E = mc^2$ [4].

The exact type and number of the resultant particles can vary depending on the specific type of particle and antiparticle interacting. For instance, the annihilation of an electron and a positron will result in the production of two or more gamma-ray photons, so as to conserve momentum as well as energy. The conversion of mass to energy in matter-antimatter annihilation events is the most efficient energy conversion process known, making antimatter a subject of potential future energy applications.

Conversely, pair production demonstrates the reverse of this process, where energy is converted into a particle-antiparticle pair. The transformation occurs when a high-energy photon, with energy exceeding the combined rest mass of the particle-antiparticle pair, interacts with a nucleus, which absorbs some momentum to ensure the conservation momentum and energy [5].

These real processes have frequently featured in science fiction, alongside other imaginative interpretations of antimatter which are more fiction than fact. This dissertation will explore the fundamental concepts of antimatter, with an aim to examine its portrayal in a science fiction example to discern the line between scientific fact and creative speculation.

2 Theoretical Foundations

Special relativity, formulated by Albert Einstein in the early 20th century, revolutionised the understanding of space, time, and the relationship between mass and energy. It postulated that time and space are relative to the observer, not absolute as believed before [6], but, more specifically, it gave birth to Einsteins $E = mc^2$. The equation defines mass-energy equivalence, setting the stage for how particle-antiparticle pairs can be created via pair production and destroyed via annihilation.

Special relativity provided tools to deal with high-speed and high-energy physics, but did not initially integrate with the principles of quantum mechanics which dealt with particles on subatomic scales. In pursuit of a quantum mechanical description that was compatible with special relativity (reconciling the Schrodinger equation with special relativity), Oskar Klein and Walter Gordon formulated the Klein-Gordon equation in 1926 [7],

$$\mathbf{E}^2 = m^2c^2 + \mathbf{p}^2c^2,$$

in terms of energy and momentum operators,

$$\mathbf{E} = i\hbar\frac{\partial}{\partial t}, \mathbf{P} = -i\hbar\nabla.$$

Squaring the energy and momentum operators, we get the following form which is second order in both time and space derivatives,

$$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2 + \frac{m^2c^4}{\hbar^2}\right)\psi = 0.$$

The Klein–Gordon equation, while successful in incorporating relativistic effects, had a limitation in that it can only correctly describe states of spin-0 particles which is inadequate for describing electrons and other Fermions with half-integer spin [7]. This limitation led Paul Dirac to seek an equation that could describe electrons in a relativistic context while also incorporating their half-integer spin.

In 1928, Paul Dirac derived the Dirac equation,

$$i\hbar\frac{\partial\psi}{\partial t} = (c\alpha\cdot\mathbf{p} + \beta mc^2)\psi,$$

where α and β are matrices responsible for incorporating the spin and the relativistic nature of the particle into the equation. This equation led to the prediction of positrons due to its negative energy solutions [7].

Both the Klein-Gordon equation and the Dirac equation had negative energy solutions, but due to the Klein-Gordon equation being second order in time they corresponded to negative probabilities, which isn't physically meaningful as negative probabilites would imply a less than zero chance of occurrence. Dirac had made an equation which was linear in time and space which maintains a positive definite probability density (like the Schrodinger equation) allowing him to make the prediction of the existence of a "Dirac sea" .

Dirac proposed that a theoretical sea, made from an infinite number of electrons, filled a vacuum. The electrons supposedly occupied all negative energy states according to the Pauli exclusion principle [8]. When an electron is excited from the sea to a positive energy state, the vacancy made would behave as a particle with positive energy and opposite charge - a hole. This hole was interpreted as an antiparticle.

Despite predicting an infinite negative charge density in the vacuum, which isn't experimentally observed, the Dirac sea correctly predicted the existence of antiparticles and acted as a stepping stone to modern interpretations of antimatter.

3 History of Antimatter

3.1 Subatomic Antiparticle Discoveries

Theoretical physicists like Dirac laid the foundational equations predicting the existence of antimatter, but it was the work of experimental physicists that have given us the understanding we have of antimatter today.

In 1932, less than four decades after Arthur Schuster's first speculation of antimatter, the positron was discovered by Carl Anderson [9]. This was a pivotal moment as it provided the first concrete evidence of antimatter, validating the Dirac equation's predictions.

The subsequent discovery of antiprotons in 1955 by Emilio Segrè and Owen Chamberlain [10] and antineutrons the next year in 1956 by Bruce Cork [11] reinforced the fundamental symmetry of nature, that for every particle an antiparticle counterpart exists, and opened the door to experiments with more complex forms of antimatter. The discovery of the antideuteron in 1965 at CERN [12] was the first example of more complex forms of antimatter, antinuclei.

3.2 Symmetry Discoveries

Before the discovery of the antideuteron, Dr Chien-Shiung Wu, in partnership with Tsung-Dao Lee and Chen-Ning Yang, made the first discovery that not all symmetries were conserved. The Wu experiment, conducted in 1957, countered the prevailing assumption of universal parity conservation (mirror image transformations), showing that the weak force distinguishes between left and right [12]. The same experiment was also able to show that charge symmetry could be violated. Before these experiments, it was thought that the laws of physics were invariant for charge and parity transformations. This was the first experimental proof of a broken fundamental symmetry in physics, it opened the door to the realisation that other symmetries could also be broken under certain conditions.

To solve these violations, Lev Landau proposed that the laws of physics should remain invariant under a combined operation of charge conjugation (replacing a particle with its antiparticle) and parity transformation (reflecting in a mirror) - coined CP symmetry [13]. However, in 1964 James Cronin and Val Fitch demonstrated CP violation in neutral kaon decay [12], illustrated in Figure 3. This revealed an intrinsic asymmetry in the laws governing matter and antimatter, a potential explanation for the matter-antimatter imbalance in the universe.

3.3 Advancements in Confinement and Anti-atom Research

The 1980s brought advances in magnetic confinement techniques, allowing for longer storage times of antiparticles and enabling in-depth studies of their properties.

A significant milestone was achieved in 1983 with the activation of the Antiproton Accumulator at CERN,where antiprotons were generated, cooled and confined into a dense core [14]. Shortly after in 1985, the first antiproton was stored in a Penning trap, a device which uses electric and magnetic fields to store charged particles [15]. This helped make more precise measurements of the antiprotons mass.

In 1995, the first antiatom was created at CERN, antihydrogen [12]. With the Antiproton Decelerator and experiments such as ATHENA and ATRAP, researchers at CERN were able to produce larger numbers of antihydrogen atoms and trap them for longer periods, facilitating more in-depth studies. This led to the demonstration in 2023 that antihydrogen atoms fall towards the Earth when subjected to the Earths gravity, just like ordinary matter [16].

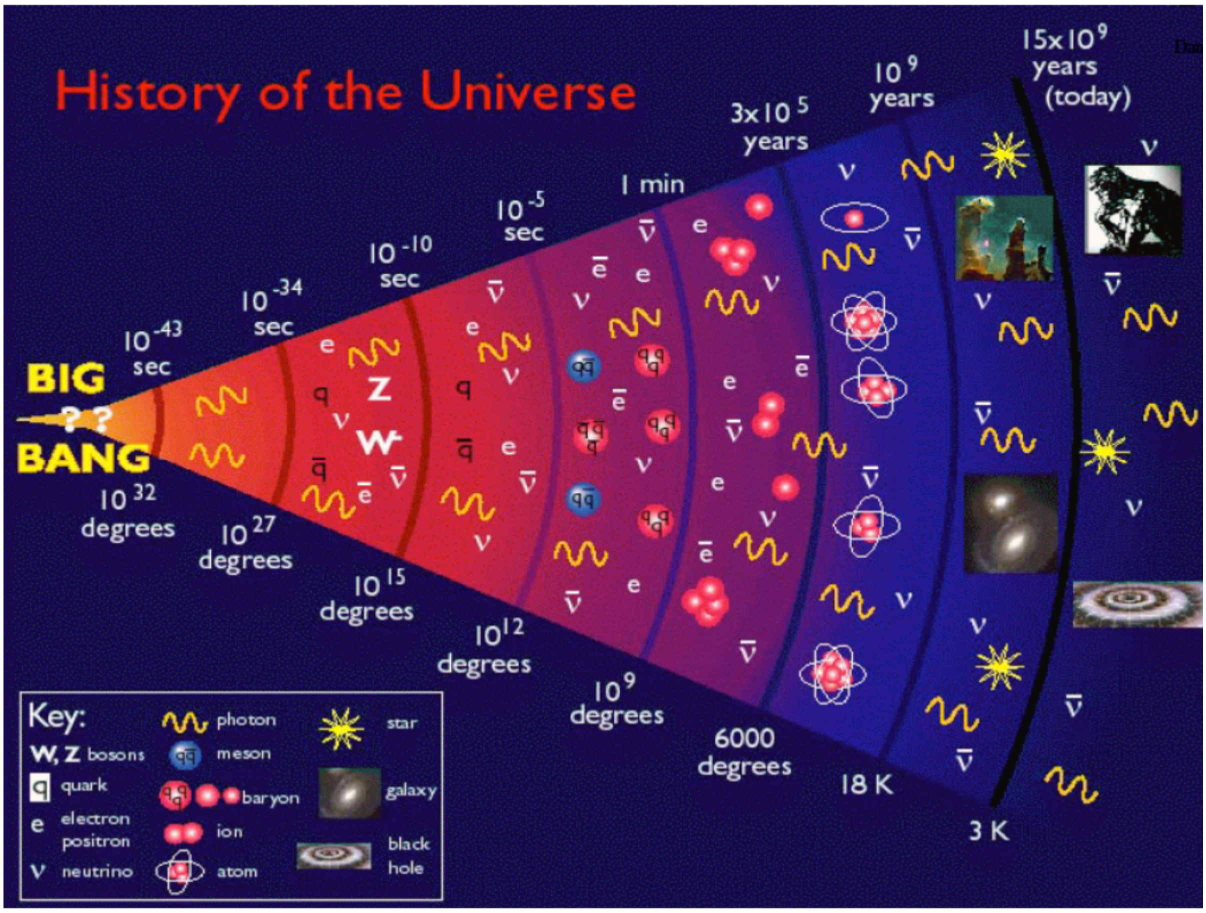

Figure 2: A brief history of the universe [18]

4 Matter-Antimatter Imbalance

4.1 Where is all the antimatter?

In the early universe, the Standard Model posits that the Big Bang should have produced matter and antimatter in equal quantities through pair production. [17]. However, the observable universe tells a story of a universe nearly entirely dominated by matter.

If antimatter were present in any significant quantity compared to matter, we should be able to detect it as it navigates through the cosmos annihilating with matter along the way. However, we have not observed the characteristic gamma rays that are distinct to annihilation events.

Baryogenesis, a physical process theorised to have occurred in the early universe, suggests a mechanism led to a slight asymmetry in baryon number that resulted in an excess of matter over antimatter. The excess if often quantified as a surplus of one part per billion [19]. This excess, after the extensive annihilation of particle-antiparticle pairs, led to the predominance of the baryonic matter that constitutes the observable universe.

4.2 Sakharov conditions for an imbalanced universe

The Standard Model can integrate baryogenesis and the resulting asymmetry, yet it does not align with the extent of asymmetry we observe. The Sakharov conditions provide a guideline for theories that go beyond the Standard Model. They are conditions that need to have been met in the early universe for an asymmetry to develop, and are as follows [20]:

1. Processes must exist that violate baryon number conservation, allowing for the conversion between baryons and antibaryons.

The first condition requires the laws of physics to permit reactions where the number of baryons can change. These processes are not part of the standard model and have not been observed experimentally. An example of one of these processes is the theoretical decay of a proton into lighter subatomic particles. This is a prediction of the Grand Unified Theory, which extends the Standard Model by unifying the electromagnetic, weak and strong forces under a single umbrella [21]. The fact it has not been observed may be attributed to a protons hypothetical half-life, which is greater than the current age of the universe.

2. Processes governing particle interactions must occur out of thermal equilibrium, allowing an asymmetry to develop and persist.

When the baryon number-violating processes occurred, the universe must not have been in thermal equilibrium. If the universe was in thermal equilibrium, any process that is responsible for producing excess baryons would be balanced by the reverse process that would occur at the same rate. Only out of thermal equilibrium would the imbalance be preserved.

3. Processes must exist that allow for Charge conjugation (C) and Charge-Parity (CP) symmetry violations, ensuring the laws of physics are not the same for matter and antimatter.

C symmetry states that the laws of physics should remain invariant when a particle is replaced by its antiparticle. CP symmetry extends this concept by stating the laws of physics should remain invariant under the combined operation of replacing a particle with its antiparticle and a parity transformation (a mirror image transformation). Violation of these symmetries allows for differences in the laws of physics between matter and antimatter, which is crucial for processes that could lead to the dominance of matter in the universe.

4.3 CP Violation

CP violation allows for the possibility of a universe that favours the abundance of either matter or antimatter. As detailed in Section 3.3, the decay of neutral kaons in 1964 was the first evidence that such CP asymmetries exist in nature. Subsequent experiments, such as BaBar and Belle, have observed CP violation in B meson decays [22].

CP violation is predicted by the Standard Model via the Cabibbo-Kobayashi-Maskawa (CKM) matrix for quarks. The CKM matrix deals with flavour transitions in weak decays, such as a down quark changing to an up quark. The complex phase in the matrix introduces CP violation as it leads to a difference in transition probabilities between quarks and their corresponding antiquarks - the probability of quark of flavour x decaying into a quark of flavour y is different to the probability of the antiquark of flavour $\bar{x}$ decaying into the antiquark of flavour $\bar{y}$ [23].

The CKM matrix's prediction for CP violation are very small, and the amount it predicts is not sufficient to account for the observed matter-antimatter imbalance. This suggests that there are additional sources of CP violation beyond what the Standard Model describes

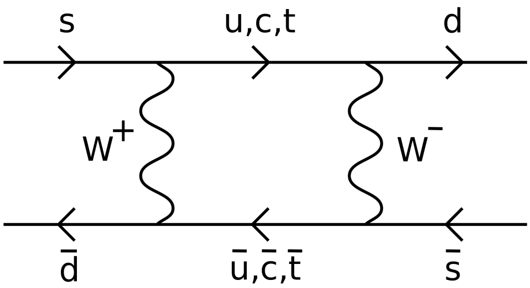

Figure 3: Feynman diagram showing a neutral kaon, K^0, decaying into its antiparticle $\overline{k}^0$ [24]

5 Ongoing Experiments

5.1 Leading Accelerator-Based Physics Experiments

Particle accelerators are an indispensable tool for investigating antimatter. Often kilometers in length, these machines accelerate subatomic particles close to the speed of light, giving rise to high energy collisions that we can study.

The European Council for Nuclear Research (CERN) are at the forefront of this technology. The Large Hadron Collider (LHC) and Antiproton Decelerator (AD) at CERN have provided unprecedented insights into antimatter through experiments such as ALPHA, GBAR and LHCb.

Figure 4: Map of the LHC, situated on the border of France and Switzerland [25].

ALPHA creates and stores antihydrogen atoms by taking antiprotons created and slowed down from the AD and combining them with positrons from a radioactive source. These are then compared with hydrogen atoms so that fundamental symmetries between matter and antimatter can be studied. It achieved the first ever trapping of antihydrogen atoms in 2010 [26], and in 2011 managed to trap antihydrogen atoms for over 16 minutes [27]. In 2023, ALPHA demonstrated that antihydrogen atoms respond to gravity the same way as regular matter by confining the atoms in a magnetic trap, and then turning the trap off and seeing where the atoms annihilate [28].

In contrast to ALPHA, the GBAR experiment specifically aims to measure the free fall acceleration of antihydrogen atoms under gravity. Utilising the AD again, antihydrogen ions with a positive charge are produced, cooled and then dispossessed of the extra positron to create a neutral antihydrogen atom. This atom is then dropped and the time taken to annihilate with the container is recorded . Although not yet proven, they aim to test the Weak Equivalence Principle, that states that gravity should effect all particles in the same way [29].

While ALPHA and GBAR focus on the behaviour of antihydrogen under gravity, LHCb, also located at CERN seeks to understand the matter-antimatter imbalance. It has built on the work of other international experiments, Belle and BaBar, where CP violations in B mesons where discovered in 2001, confirming the predictions of the CKM matrix detailed in Section 4.3 [22]. The LHCb creates high energy proton-proton collisions to study particles containing bottom quarks, like B mesons. Due to operating at higher energies and collision rates than its predecessors, LHCb is able to explore rarer decay paths previously inaccessible, allowing for the study of physics beyond the Standard Model.

5.2 Space-Based Particle Physics Experiments

Space-based experiments offer unique advantages over earth-bound laboratories. The vacuum of space provides an interference-free environment, which helps with accurate detection of naturally occurring antimatter in cosmic rays.

Two methods are used to investigate antimatter, direct particle detectors and gamma-ray observatories. Direct particle detectors like the Alpha Magnetic Spectrometer (AMS) and the Payload for Antimatter Exploration and Light-nuclei Astrophysics (PAMELA) directly measure the components of cosmic rays, whereas gamma-ray observatories, such as the Fermi Gamma-ray Space Telescope, observe gamma rays.

Cosmic rays, high energy particles, are a significant source of antimatter. The AMS, mounted on the International Space Station, and PAMELA, a satellite-based mission launched in 2006, both utilise a magnetic spectrometer to study cosmic rays. The paths of charged particles within the magnetic spectrometer are analysed and their charge and momentum are determined with great accuracy.

The AMS aims to capture antimatter, specifically in the form of antinuclei. It has not yet detected any antinuclei, but it has observed an excess of positrons in cosmic rays [30]. This could be indicative of nearby pulsars, rapidly rotating neutron stars that are capable of accelerating particles to very high energies, who's emitted particles are detected as part of the cosmic ray flux.

PAMELA studies cosmic rays in a near-earth environment and focuses on detection of antiprotons and positrons across a broad energy range. Its orbit, within the Earth's magnetosphere (the region of space where the dominant magnetic field is that of Earth's), has allowed it to detect an excess of antiprotons resulting from collisions with particles in the Van Allen belt, a region of energetic charged particles that have been trapped by Earth's magnetic field [31]. This confirmed that cosmic rays can interact with the Earth's upper atmosphere and produce secondary particles like antiprotons which then become trapped in the Van Allen belts.

Gamma rays are the most energetic form of light that are produced by high-energy processes, including annihilation between matter and antimatter. The Fermi Gamma-ray Space Telescope, like PAMELA, is a satellite based mission that entered orbit in 2008. It contains two primary instruments: the Large Area Telescope (LAT) and the Gamma-ray Burst Monitor (GBM).The LAT detects gamma rays by tracking the paths of particles that are created when rays interact with its detectors, while the GBM observed gamma-ray bursts which are amongst the most energetic and short events known. Through collecting data on energy, arrival time and direction of the gamma rays it encounters, it has mapped the gamma-ray sky shown in Figure 5.

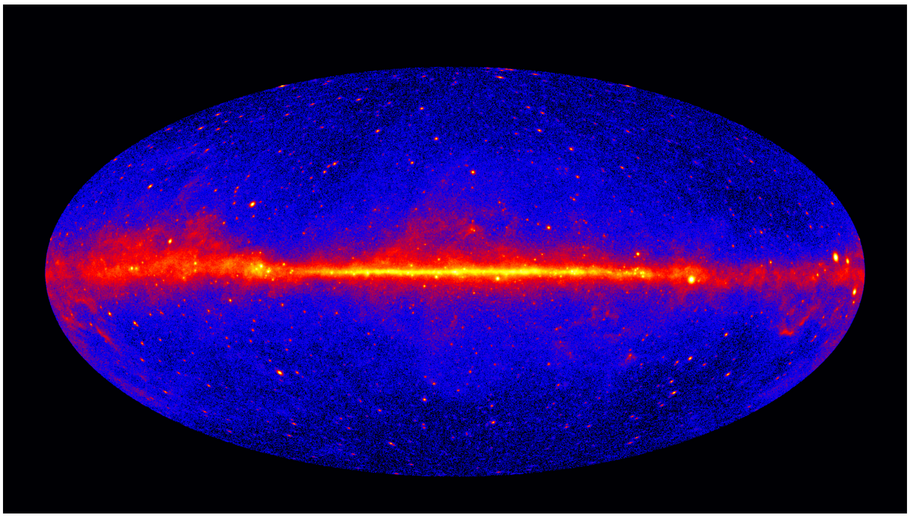

Figure 5: The Fermi LAT 60-month image, constructed from front-converting gamma rays with energies greater than 1 GeV. The bright band of diffuse glow along the map's center marks the central plane of our Milky Way galaxy [32].

6 Antimatter in Media

Soon after the concept of antimatter was introduced in theoretical physics, it became a staple in science fiction. As early as 1937, antimatter featured in John Clark's story,*Minus Planet* [33]. More notably it has appeared as the basis for for separate universes in *Doctor Who*, weapons in Scott Card's *Ender's Game*, and as the fuel for Warp drives in *Star Trek* which we will explore in further detail in the next section.

Science fiction authors often cherry pick real concepts from fields they are writing about. For example, in Dan Brown's *Angels and Demons*, antimatter is contained within a small canister within which is a vacuum and a magnetic field [34]. This aligns with real experiments such as ALPHA and GBAR, where magnetic confinement within a vacuum is crucial to prevent contact between matter and antimatter. Also, in *Star Trek: The Next Generation* in the episode *Silicon Avatar*, the *Enterprise* searches for a life form that leaves behind a trail of antiprotons [35]. It does this by searching for the annihilation energy that would be created when the antiprotons came into contact with matter, which is how the Fermi Gamma-Ray Telescope operates.

Needless to say, science fiction is not science. In the example from *Angels and Demons*, the antimatter is portrayed to be stationary within the canister, which does not consider the fact that magnetic fields only affect moving charges, relative to the magnetic field [36]. In the scenario from *Silicon Avatar*, they search for a gamma radiation spike at 10 KeV, which is notably less than the annihilation energy from an electron-positron pair, 511 KeV, the annihilation event with the lowest energy.

In the next section we will investigate a specific example of antimatter in science fiction and attempt to discern what features are theoretically possible and what aspects are purely fiction.

7 Fiction to Realitys

Figure 6: The USS Enterprise [37]

7.1 Warp Drive

We begin by introducing the fictional concept of the warp drive used in the *Star Trek* universe. Contrary to popular belief, the warp drive is not a conventional propulsion system. It operates on the principle of warping space-time around a spacecraft, theoretically contracting space in front and expanding the space behind allowing the ship to achieve faster than light travel [38]. Special relativity prohibits faster than light travel for any massive object, however, the manipulation of space-time is not limited by the speed of light constraint in Einstein's theory.

Annihilation's between matter and antimatter (deuterium and antideuterium) create the power needed for the *warp coils* which generate the warp field [39]. however, in this section we will not be delving into the mechanics of the warp drive. We will explore concepts of the matter-antimatter fuel that stored on the *USS Enterprise* that are grounded in real physics: how much energy is available, how it is stored and finally how the same fuel could be used to power a propulsion system.

7.2 Antimatter Production and Energy Availability

7.2.1 Initial Assumptions

According to *Star Trek: The next generation technical manual* (NGTM), antimatter is generated at fuelling facilities by *combined solar-fusion charge reversal devices.* Proton

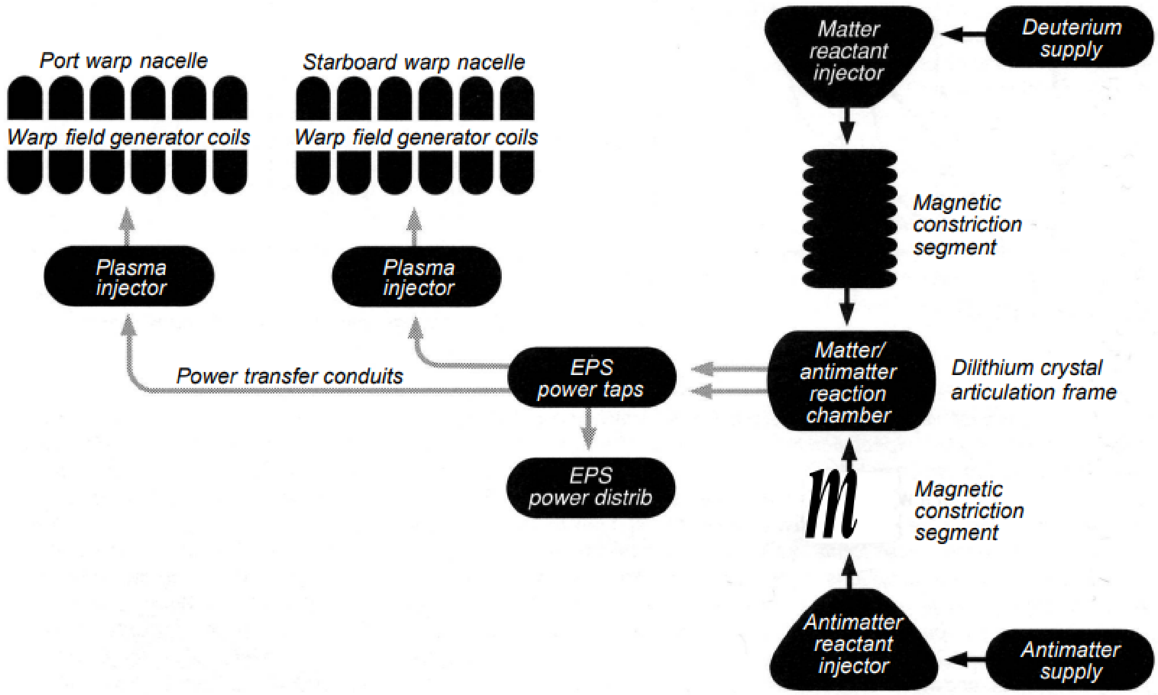

Figure 7: Diagram depicting the warp drive system utilised in starships such as the *USS Enterprise* in the *Star Trek* universe [39].

and neutron beams are converted into antideuteron ions and subsequently combined with a positron beam to produce neutral anti-deuterium [39]. As discussed in Section 1, antimatter differs in quantum numbers beyond charge, so we will assume that the charge reversal device inverts all the relevant quantum numbers.

The state of antimatter in storage is not explicitly defined, however, the warp drive system depicted in 7 mentions *"Pulsed antimatter gas flow separators"*. Given this specification, and considering its matter counterpart is stored at $10^6 K$ [39], we can infer a high temperature gaseous state of storage.

A containment issue also arises, as magnetic fields only act on charged particles [36]. To address this challenge, we can consider the storage temperature. One million kelvin is safely above the ionisation temperature of deuterium [40], so we can further assume that the antideuterium is stored as a plasma, suitable for magnetic confinement.

We also have to address the effect of the electric fields created from the positrons and ions. Within the plasma, Debye shielding will effectively remove the impact of electrical fields [41]. Electric forces exerted by individual particles approximately cancel each other due to a symmetrical distribution of charges.

7.2.2 Energy Calculation

Famously stated in the opening of the original *Star Trek* series, the *USS Enterprise* spends five years in its deep space mission, implying only a single fuelling. According to the NGTM, there are thirty storage pods on ships of the same size as the Enterprise, each with a maximum capacity of $100m^3$, totalling $3000m^3$ [39].

We can treat the antideuterium plasma as an ideal gas and use the ideal gas law, $PV = nRT$ to find the number of moles within the plasma. We have values for everything but pressure, where we will reference the Alcator C-Mod tokamak at MIT, where the

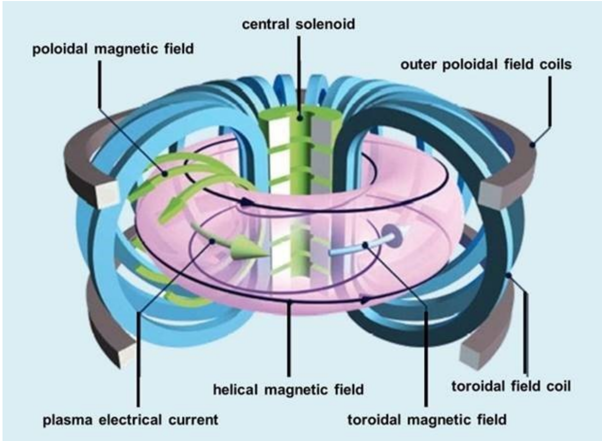

Figure 8: Illustration of a tomokak design [45]

record for the highest plasma pressure was achieved 2.05 atm [42]. Given the remarkable technological advancements evidenced in *Star Trek* between the 22^{nd} and 24^{th} centuries, it is reasonable to assume that such pressures could be routinely attained, so we will use this value as a lower bound.

Using deuterium's molar mass (identical to antideuterium) of 2.01 grams per mole, and assuming a quasi-neutral plasma (an equal number of positrons to nuclei) we determine the mass ins a single storage pod to be approximately 5.031 grams. For perspective, the total artificial production of antimatter at Fermilab and CERN amounts to a measly 16 nanograms in comparison [43].

Pairing these 5 grams of antideuterium with an equivalent 5 grams of deuterium, the energy from the annihilation is $\sim 9.043 \times 10^{14}$ Joules with all thirty pods yielding $\sim 2.713 \times 10^{4}$ terajoules. For context, the *Little Boy* bomb used in the bombing of Hiroshima released an estimated 54 terajoules [44]. The available energy from the annihilation reactions is equivalent to detonating up to 500 *Little Boy* nuclear bombs.

7.3 Containment issues

7.3.1 Initial Assumptions

Containment of the antimatter onboard a starship is a critical element in the design, any lapse in storage would lead to uncontrolled destruction. This is seen in the *Star Trek: The Next Generation* episode *Contagion*, where the *USS Yamato* experiences a catastrophic failure of its warp drive containment system leading to the antimatter stored to come into uncontrolled contact with matter which completely destroys the ship [46].

We will now realise the storage pods we have introduced using tokamaks. A tokamak is able to create stable, circular orbits for charged particles, minimising their interaction with the container walls and reducing the risk of annihilation events. The deign is illustrated in Figure 8

Due to difficulties involved with scaling down tokamak devices, we will assume the stated available volume of $100m^3$ in each storage pod corresponds to the plasma volume - the volume occupied by the plasma. This is conveniently equal to the plasma volume of the Joint European Torus (JET), the worlds current largest operational magnetic confinement plasma physics experiment [47]. We will use the dimensions of the JET as a basis for the dimensions of our storage pods.

Tokamak designs are mainly used in nuclear fusion experiments like JET and the Alcator C-Mod tokamak at MIT. Tokamaks designed only for magnetic confinement of antideuterium would have a distinct setup from fusion-oriented tokamaks, as the focus shifts from achieving temperatures of over 150 million kelvin [48] required for fusion reactions, to long term containment of plasma at 1 million kelvin. Within the futuristic context of Star Trek, where advanced technology is a hallmark, we can make several idealised assumptions specific to our tokamak design. Firstly, the antideuterium plasma is devoid of any impurities, ensuring maximal efficiency in plasma behaviour. Secondly, the magnetic confinement system is perfect, all plasma is maintained in a state of non-contact with any matter; necessary for this method to be viable. Lastly, the plasma's velocity is non-relativistic which reduces the likelihood of complications associated with relativistic effects, such as mass increase and time dilation.

7.3.2 Energy requirements

Tokamaks require substantial energy input, primarily for powering the electromagnets essential for magnetic confinement. How much power would thirty tokamaks onboard the *USS Enterprise* need?

To address this, our primary focus will be on the energy necessary for magnetic confinement, rather than maintaining the plasma temperature. The energy required to maintain plasma temperature, while not insignificant, is substantially lower than that for magnetic confinement. For example, JET uses approximately 4 megawatts for plasma heating, compared to the much higher demands for magnetic field generation of 150 megawatts [49].

It is pragmatic to focus on the primary energy consumer, the magnetic confinement system, to simplify the estimation.

Superconducting Electromagnets

As stated above, the JET tokamak requires 150 MW for its electromagnets that are responsible for the magnetic confinement [49]. Thirty tokamaks operating at this power for five years would require a total of 7×10^5 terajoules, larger than the amount of energy available from the fuel itself. A more efficient method must be employed.

In our design, superconducting electromagnets can be used to reduce the power required to maintain the magnetic fields. Superconductors are materials that can conduct electricity with zero resistance [50]. A current can be sustained indefinitely without power input as there are no energy losses from resistance, meaning we can create stable, high-intensity magnetic field without the need for continuous power input.

Current superconductors require cooling to very low temperatures, below their critical temperature, to exhibit superconducting properties. For example, the International Thermonuclear Experimental Reactor (ITER), currently being constructed in France, is designed to use superconducting coils made of niobium-tin (Nb3Sn) and niobium-titanium (Nb-Ti) to create its magnetic field [51]. Niobium-titanium requires cooling to 4 Kelvin using liquid helium to get into its superconducting regime.

Calculating an exact power value for a theoretical cryogenic system is challenging due to the complex interplay of various thermodynamic factors and the extreme precision required at ultra-low temperatures. It is more pragmatic to design a system that leverages the conditions of space and compare it with a less efficient example of the cryoplant used to cool the superconducting electromagnets at ITER, which requires 35 megawatts at full capacity [52].

For our design we will assume a low-temperature superconductor made of niobium-titanium, cooled by superfluid helium, is used for the electromagnet. Although room temperature superconducting electromagnets are shown to exist in the *Star Trek* universe [53] and would eliminate the need for a complex cooling system , one has not yet been found in reality.

Superfluid helium has several advantages over liquid helium: it can maintain a temperature of 1.8 kelvin leading to a higher critical current density in the superconductor (the maximum current density it can withstand without losing superconductivity), its higher density resulting is smaller storage tanks, and its zero viscosity and high thermal conductivity leading to more effective heat transfer from the magnets [54]

To maintain the low temperature of the superconducting electromagnets, a combination of cryogenic storage, thermal management and circulation systems are needed to manage the superfluid helium.

Storage and Insulation

The superfluid helium is stored in an insulated dewar. This dewar is constructed using multi-layered superinsulation materials, selected for their exceptionally low thermal conductivity . We can utilise the vacuum of space to encase the dewar and act as an insulating medium, minimising external heat transfer to the dewar. To dissipate any residual heat absorbed by the dewar, radiative cooling panels, designed with high-emissivity surfaces, can be placed on the dewar's surface with an orientation designed to maximise exposure to the coldness of space.To maintain the liquid phase, a porous plug phase separator is integrated, which only allows the escape of helium gas, even in zero gravity [55].

The dewar's design effectively minimises thermal energy transfer, crucial for maintaining the superfluid state of helium.

Fountain Effect Circulation System

The circulation system exploits the fountain effect phenomenon in superfluids. Applying heat to a localised area creates a pressure differential due to zero viscosity and the high thermal conductivity. This differential induces flow from cooler to warmer regions, creating a fountain like spout that circulates the superfluid helium without the need for any moving parts [56].

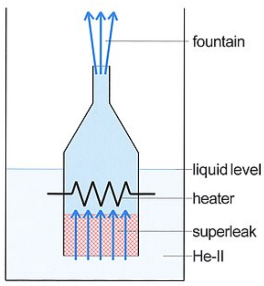

Figure 9: Demonstration of the fountain effect. A capillary tube is "closed" at one end by a superleak and is placed into a bath of superfluid helium and then heated. The helium flows up through the tube and squirts like a fountain [57]

Heat Exchange and Refrigeration Cycle
The helium would pass through a heat exchanger system where it absorbs heat from the electromagnets and evaporates. The gaseous helium then undergoes a refrigeration cycle, where it is re-liquefied and then routed back into the dewar.

A single storage pod would likely require less power than the cryoplant at ITER for several reasons.

The vacuum of space being used for thermal insulation and radiative cooling would greatly reduce power required for refrigeration. Shared infrastructure for the thirty storage pods would increase efficiency and reduce the total number of components required. Bulk storage of the coolant would be more effective as there is a reduced relative surface area through which heat can enter. Energy efficiency of cooling mechanisms generally improve with increased scale, so a centralised refrigeration system would be beneficial.

We can therefore assume 35 megawatts is maximum value for the power requirements for cooling the electromagnets. This is effectively the power required for magnetic confinement as the power to maintain the magnetic fields is negligible. For all thirty pods, this would amount to 1050 megawatts, a significant reduction from 4500 megawatts required for thirty 'JET-like' tokamaks.

However, this brings into focus the transformative impact that high-temperature superconductors could have. With their implementation, the energy required would drop to near-zero in comparison to the design explored in this section.

7.4 Propulsion system

In contrast to the warp drive, a propulsion system using antimatter fuel, while highly advanced and not yet feasible, aligns more closely with established scientific principles. Rocket propulsion is grounded in well-established principles of physics, namely conservation of momentum and energy.

7.4.1 Basic Principle

Antimatter propulsion systems are theoretical machines that harness the energy from annihilations. Annihilation's produce high-energy particles and photons, which can create significant thrust when directed correctly.

Utilising the products of annihilations directly for thrust is a difficult task. Photons, along with other neutral charge resultant particles, cannot be redirected with electric or magnetic fields, making it hard to harness their momentum in a controlled manner.

7.4.2 Design Considerations

Specific impulse is a measure of the efficiency of a propulsion system, defined as the thrust produced per unit weight flow rate of the propellant, $I_{specific} = \frac{F_{thrust}}{\dot{m} \times g_0}$ [58] and is generally used to compare the performance of different propulsion methods. Engines with a high specific impulse often produce lower thrust or acceleration, as they expend the propellant more efficiently over a longer duration.

The choice between high thrust and high specific impulse varies; for deep space missions, gradually reaching high velocities with efficient long term fuel usage is desirable. A proton-antiproton beam core engine is a theoretical engine design that will produce a high specific impulse, effectively utilising the antimatter fuel.

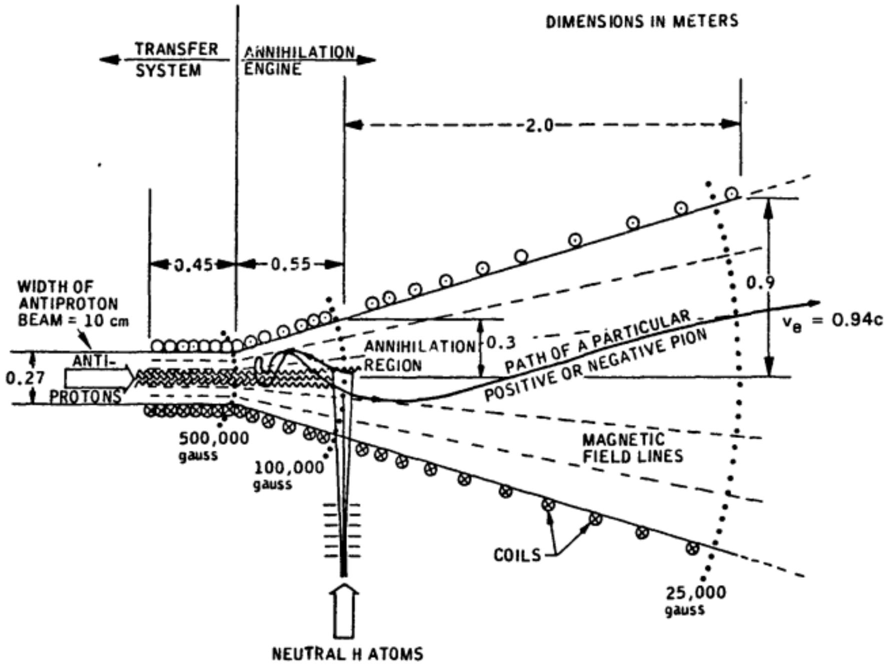

Figure 10: Antiproton-proton beam core rocket [59].

7.4.3 Antimatter Beam Core Engine

This engine harnesses the kinetic energy produced when antiprotons and protons annihilate. Approximately 64% of the rest mass in these annihilations is converted to kinetic energy, while the remaining 36% constitutes the mass of the resultant particles. Since thrust is created from the momentum of particles moving through an exhaust, the annihilation allows us to make use of all of the mass energy [58]. In antiproton-proton collisions, the most likely outcome is the production of pions, both charged and neutral, with the neutral pions rapidly decaying into gamma rays.

The core mechanism of thrust generation is redirection of charged particles from annihilations through the exhaust. The design given in *Simulation of an Antimatter Beam Core Engine for Space Travel* uses a solenoid, which forms its outer cylindrical shell, to create a non-uniform magnetic field which weakens as it approaches the exhaust, allowing for redirection of charged particles through the exhaust [58].

A simulation was made using this design to find the specific impulse of the engine. The parameters (kinetic energy of antiprotons, solenoid length and radius, minimum and maximum magnetic field values at either end of the solenoid and the location of annihilation events) were optimised for the state that maximised the product of impulse and efficiency. In this optimised state, the engine produced a specific impulse of $(2.49 \pm 0.08) \times 10^6$ seconds, which is orders of magnitude higher than that produced by chemical rockets ranging from 240 to 400 seconds [58]. With current state of the art beam densities of 10^7 antiprotons per second, the engine would produce 9.78×10^{-13} Newtons of thrust [58].

Using the relativistic Tsiolkovsky rocket equation, $\Delta v = c \tanh\left(\frac{v_{exhaust}}{c} \ln \frac{m_i}{m_f}\right)$ [60], we can apply this thrust to the *USS Enterprise*, which has a mass of 190,000 tonnes. If we take the amount of antimatter stored on board, ~ 150 grams, and equate it to a corresponding mass of antiprotons, we find a top speed of 0.39 meters per second, which is not of any use. If current state of the art beam densities are used, this would take approximately 2.8 billion millennia.

To achieve a speed of half of the speed of light, we would require 170 million tonnes of antimatter - nearly 900 times the mass of the ship on its own.

8 Conclusion

Science fiction rapidly embraced the concept of antimatter soon after is experimental confirmation by Carl Anderson in 1932. The fascination is rooted in its inherent rarity and explosive characteristics when it comes into contact with matter, releasing energy according to the mass-energy equivalence principle. These properties offer a dramatic, yet scientifically grounded, element for storytelling

Narratives have evolved in tandem with advancements in our understanding of antimatter. This symbiotic relationship often sees science fiction incorporating new scientific findings, thus serving as a reflection of contemporary scientific knowledge. Antimatter in fictional contexts frequently mirrors real-world experiments in high-energy particle physics, such as *Star Trek* incorporating antideuterium into its story a year after it had been discovered at CERN in 1965.

The depiction of antimatter as a fuel source in science fiction, such as its use on the *USS Enterprise* in Star Trek, underscores its immense theoretical energy potential; the energy equivalence of the matter-antimatter fuel stored on the *USS Enterprise* equating to the energy output of 500 *Little Boy* atomic bombs. This is a dramatic representation of the theoretical capabilities of antimatter, considering current technological limitations in antimatter production and storage.

Current experiments involving antimatter containment, such as those at CERN, involve complex magnetic traps and ultra-cold temperatures. The concept of high-temperature superconductors, though not yet realised other than in the *Star Trek* universe, presents a theoretically efficient solution for antimatter containment. They could be considered necessary for long term containment of antimatter, reinforced by the result that the energy consumption of antimatter storage pods on board the *Enterprise* are comparable to the energy stored in the matter-antimatter fuel itself.

Our investigation into the utilisation of antimatter as a propulsion system highlights the significant gap between science fiction and the current scientific feasibility of antimatter application, even in grounded scientific concepts like rocket propulsion. 150 grams of antimatter, over nine million times the amount synthesised at Fermilab and CERN, is still not sufficient to provide any meaningful speeds that chemical rockets cannot provide.

The forward thinking nature of science fiction writers is an argument that they are ahead of their time; even Arthur Schuster had to 'dream about the unknown' to hypothesise antimatter. This visionary aspect of fiction serves as a catalyst for scientific inquiry.

Word Count: 5983

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