Chapter

Matter/Anti-Matter Propulsion

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Abstract

One of the key potential technologies for generating high speeds in space is matter/anti-matter annihilation. With the Compton effect, if positrons and electrons can be annihilated in a controlled way, and in sufficient quantities, then humans are able to achieve relativistic speeds in space. This chapter describes a technology, matter/anti-matter propulsion, which is likely to enable the generation of relativistic speeds in space. To explain this technology, background information and prior efforts to promote matter/anti-matter annihilation as a propulsion source are introduced. Further, based on recent experiments conducted in the United States and Germany, the theoretical feasibility of generating relativistic speeds in space is explained. Finally, initial experiments designed to evaluate matter/anti-matter propulsion are described.

Keywords: matter, anti-matter, annihilation, Compton effect, relativity, relativistic speed, photon rocket

1. Introduction

This book is an outgrowth of the reality of the limitations of the speeds of chemical rockets. As Tsiolkovsky demonstrated over 100 years ago, the speeds achievable by chemical rockets are, in practice, limited by the exhaust speeds of their thrusters and the energy density of their propellants, because chemical rockets must push all their fuel as they accelerate [1].

Many technologies have been proposed to propel spacecraft faster than can be achieved with chemical rockets: ion propulsion, fusion propulsion, space sails, etc. This chapter is concerned only with matter/anti-matter propulsion. Based on fairly recent experiments conducted at Lawrence-Livermore National Laboratory (LLNL) [2] and the Max Planck Institute for Plasma Physics (MPIPP) [3], matter/anti-matter annihilation appears to be a promising candidate for dramatically exceeding speeds capable by chemical-rocket technologies. Most importantly, it appears that matter/anti-matter annihilation is a likely propulsion source for generating relativistic speeds in space—speeds that are a significant fraction of the speed of light.

In order to understand the possibilities of matter/anti-matter propulsion, it is necessary to understand: (1) the nature of light, matter, and anti-matter; (2) how light and matter interact; (3) how anti-matter can be generated; and (4) how the generation and annihilation of matter with anti-matter can propel a spacecraft. With these principles established, it is possible, as a theoretical matter, to anticipate the speeds that may be reached using matter/anti-matter propulsion.

The project of realizing matter/anti-matter propulsion is exciting, and the impact of successful development of this technology would be profound. With matter/anti-matter propulsion, the nearest stars are within our reach. This chapter is intended to show that the technology necessary for interstellar travel has already been demonstrated in the laboratory.

To the greatest extent possible, this chapter starts with basic concepts and works through to likely theoretical outcomes, with the intention to be readable and understandable for a general audience. It is hoped that scientists and engineers who are well-versed in these basic concepts will, with understanding, tolerate the simplest information provided here.

2. The problem: the Tsiolkovsky equation and its implications

The basic structure of a rocket is well-known. Demonstrating Newton's Third Law ("For every action, there is an equal and opposite reaction"), when a gas (particularly, a hot, expanding gas) exists within an open-ended chamber, the unequal distribution of forces within the chamber causes the gas to push the rocket forward. **Figure 1** shows the basic application of Newton's Third Law in a "balloon" rocket; chemical rockets work the same way.

Chemical rockets work by burning a fuel (such as liquid oxygen, or a solid combustible compound) inside a thruster. The hot, expanding gases in the thruster push the rocket forward. There is a practical limit to the speeds that can be achieved by chemical rockets, however, because they must "push" all of their own fuel. In 1896, Konstantin Tsiolkovsky, the great Russian rocket scientist, determined the formula for calculating a change in rocket velocity. The formula is:

$$\Delta v = v_e \bullet \ln\left(m_0 / m_f\right), \tag{1}$$

where v_e is the velocity of the rocket's exhaust, m_0 is the initial mass of the rocket, and m_f is the mass of the rocket at the end of the burn [4].

Importantly, because the change in speed of a rocket is a logarithmic function of the ratio of the change in the rocket's mass, and because the change in speed is a direct function of the exhaust's velocity, there is a practical limit to the speeds achievable by chemical rockets. The more mass the rocket must have (in fuel weight), the less it is able to accelerate. For that reason, much of twentieth-century rocket technology involved

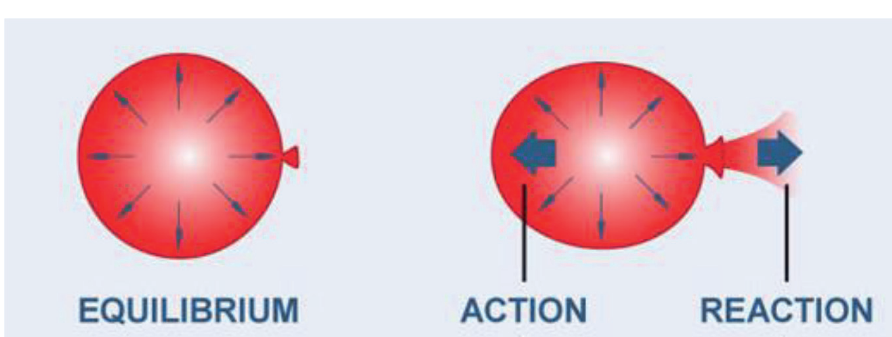

Figure 1.
Rocket principle (courtesy Mustang Publishing).

increasing both the velocity of exhaust and the energy density of fuel, while building multiple stages to achieve escape velocity. (When a stage drops off, the mass of the rocket is decreased, increasing potential acceleration of the rocket for the next given period of time.) The United States' Apollo V rocket, with its dense fuel (liquid oxygen), high-speed fuel pumps, and its multiple stages, is a perfect example of the practical implications of Tsiolkovsky's rocket equation when applied to chemical rockets.

Matter/anti-matter rockets work under the same principle as chemical rockets, only light itself (specifically, 511-keV gamma rays) is the propellant. The velocity of the "exhaust" of a matter/anti-matter rocket is the speed of light; the change in mass of the rocket as it accelerates is virtually zero. For that reason, matter/anti-matter rockets, as a practical implication of Tsiolkovsky's equation, given enough time, can achieve speeds that are a significant fraction of the speed of light.

3. Fundamental background: the nature of matter, anti-matter, and light

3.1 The nature of matter & anti-matter

Matter is the "stuff" that you know. It's the material that you can touch and feel, that you can breathe. It's the material that makes you.

In a basic way, matter is composed of protons, neutrons, and electrons. Protons have a positive electrical charge, neutrons have no electrical charge, and electrons have a negative electrical charge. Protons and neutrons are heavy, and electrons are very light, but electrons are not weightless. **Figure 2** shows a "planetary model" of a helium atom, with electrons "orbiting" the nucleus of the atom.

Anti-matter is the mirror opposite of matter. In a basic way, it is composed of anti-protons, anti-neutrons, and positrons. ("Positron" is the "P" in "PET" scan, for example.) Anti-protons have a negative electrical charge, anti-neutrons have no electrical charge, and positrons have a positive electrical charge. Anti-protons and anti-neutrons are heavy, and positrons are very light. But, as with electrons, positrons are not weightless. **Figure 3** shows an anti-matter "helium" atom, a mirrored concept of a helium atom.

When our universe was first created, there were probably equal amounts of matter and anti-matter. For some reason, our universe ended up being composed almost entirely of matter. Nonetheless, when an electron and a positron collide, they are annihilated—reduced to nothing. No mass, no electrical charge. But they do expel two

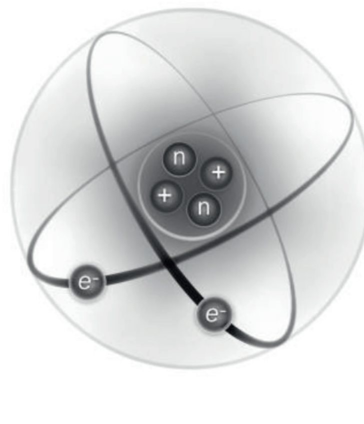

Figure 2.
Basic model of a helium atom (courtesy Mustang Publishing).

Figure 3.
Basic model of an anti-helium atom (courtesy Mustang Publishing). (Note: the symbol "p+" is used to show the positron. It is used here for a general audience, for ease of understanding; it should be noted that the international scientific convention for positrons is "e+").

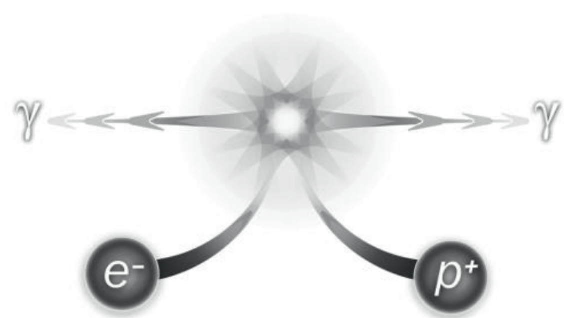

Figure 4.
Electron/positron annihilation (courtesy Mustang Publishing).

rays of light, called gamma rays ("γ"), in opposite directions, as well as a neutrino (or neutrinos—the exact number produced in an annihilation is unknown), a light, extremely fast particle with no electrical charge. The gamma rays produced in an electron-positron annihilation possess the energy of 511,000 electron volts, usually represented as "511-keV" [5]. **Figure 4** conceptualizes the collision of an electron and positron, resulting in their annihilation and the creation of two gamma rays; the resulting neutrino or neutrinos is/are not shown.

3.2 The nature of light

In addition to matter, our universe contains energy, particularly light and gravity.

Gravity is what holds you to the ground. Isaac Newton, famously, is said to have thought of gravity as the force that causes an apple to fall from a tree and hit the ground.

Light is the energy that lets you see, or makes a radio work, or makes an x-ray machine work. In a basic way, light can be thought of as a bit like the waves on a lake. Our understanding of light-as-a-wave began in 1803 with Thomas Young, who conducted the first experiment that we now call the "double slit" experiment [6]. It showed that light, traveling through two separate, but close, slits, creates a pattern that is just like the pattern made by waves of water after a splash hits near two piers.

But light can also be thought of as particles—a thing that goes from one place to another. The light from distant stars, for example, looks to us like a single point, without a wave aspect at all. Albert Einstein received the Nobel Prize in Physics in

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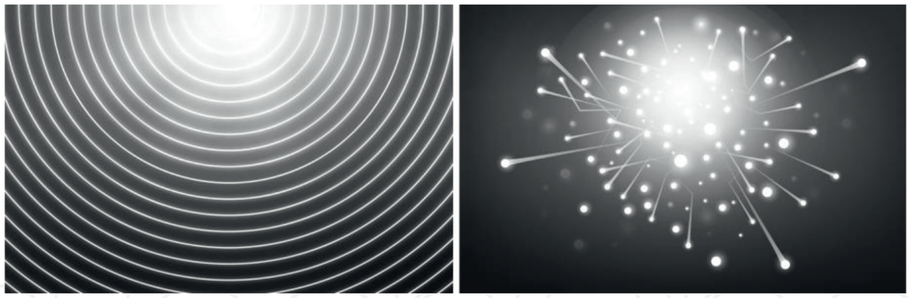

Figure 5.
Light as a wave, light as particles (courtesy Mustang Publishing).

1921 for his discovery of the "photoelectric effect," which demonstrates that light, in some ways, acts as if it is made of particles.

So light has a dual nature. In some ways, it's like a wave, and in some ways it's like a particle—like a golf ball hit by a golf club. Thinking of light as a particle helps one analogize matter/anti-matter rockets with chemical rockets. Instead of the gaseous particles that propel chemical rockets, matter/anti-matter rockets use light "particles" to propel the rocket forward. **Figure 5** visualizes our two ways of thinking about light: light as waves and lights as particles.

4. Interactions between light and matter, including the Compton effect

When we think of light as particles, we call these particles photons. The energies of photons constitute a continuous spectrum, from lowest energies to highest (and longest wavelengths to shortest), called the "electromagnetic spectrum": radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma rays.

Photons interact with matter in a number of ways. Photons can be absorbed by matter. Photons can be reflected by matter. At higher energies, light can push matter. Arthur Compton won the Nobel Prize in 1927 for demonstrating that X-rays push the electrons of matter, depending upon the angle that the photons strike the electrons of the material [7]. At even higher energies, photons, in a process known as the Bethe-Heitler Process, can cause pairs of electrons and positrons to be ejected from an atom. It is generally understood that the electrons and positrons produced in the Bethe-Heitler Process arise from the "quantum vacuum" [8]. **Figure 6** shows

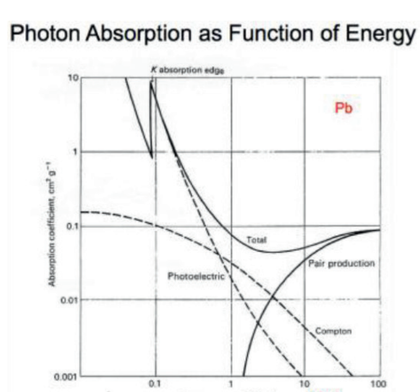

Figure 6.
Photon interaction with lead, as a function of photon energy [9].

the interaction of photons at various energies interacting with lead; the photoelectric effect, Compton scattering, and Bethe-Heitler pair production are shown (Rayleigh scattering is not separately indicated).

The electron/positron pairs generated in the Bethe-Heitler Process, and the Compton effect, where gamma rays push matter, are the two physical processes that are at the heart of matter/anti-matter propulsion. As will be discussed more fully below, in a matter/anti-matter spacecraft, a high-energy laser will generate electron/positron pairs in the Bethe-Heitler Process and then those pairs will separately be directed to a thruster where they will collide, annihilate, and generate gamma rays. When the gamma rays hit the inner shell of the thruster, the gamma rays will propel the spacecraft forward utilizing the Compton Effect and Newton's Third Law.

5. Theoretical background: the problems of paired-particle generation and storage

5.1 Origin of the idea of photon propulsion & theoretical follow-on

Eugen Sanger, a Bohemian-Austrian-German-French aeronautical engineer and scientist, is generally credited with proposing the idea of a photon-propelled spacecraft in the late 1950s [10]. He even proposed gamma rays as a source of propulsion for rockets. At that time, laser technology was barely in its infancy, and positrons were mainly understood as cosmic rays that arrive from outer space in small numbers, or from rare radioactive decay. No mechanism for generating large quantities of positrons was conceivable.

But the idea of anti-matter annihilation as a potential propulsion source of energy for space travel persisted. The attraction of the energies generated by matter/anti-matter annihilation reactions, combined with the low mass of positrons and electrons, in light of Tsiolkovsky's equation, was too powerful. Furthermore, over the ensuing decades, laser technology, positron generation (even in low numbers, like in PET scanners), fission reactors, and magnetic containment vessels (such as for fusion experiments) were developed.

By the late 1990s and early 2000s, anti-matter propulsion became a topic of increased research and discussion [11–13]. In the United States, at least two programs were undertaken to further matter/anti-matter propulsion. At Embry-Riddle Aeronautical University (ERAU), the Hyperion Project, led by Darrel Smith and Jonathan Webb, sought to advance this form of propulsion. At the conclusion of the project, in 2007, Smith and Webb concluded that the "current state of the art technology is lacking in the areas of positron production and storage techniques for these concepts to be realized any time in the near future" [14]. The prior year, the United States' National Aeronautics and Space Administration (NASA) concluded a project at its Institute for Advanced Concepts (NIAC) exploring the possibility of anti-matter-propelled spaceships. The NIAC team, like the team at ERAU, concluded that the "technical challenge of positron production," and the challenge of "storing enough positrons in a small space," persisted as obstacles for achieving matter/anti-matter propulsion [15].

5.2 Key laboratory discoveries

The difficulties with positron generation and storage did not last long.

First, in 2008, Hui Chen and others on her team at LLNL demonstrated that large quantities of positrons could be produced by high-energy, short-burst lasers striking high-Z (i.e., high-atomic-mass) targets [16]. Then, a few years later (beginning in 2015), the storage of electrons and positrons in an optimized dipole stellarator, by Eve Stenson and others on her team at the MPIPP, was demonstrated [3].

With these two discoveries, the primary obstacles identified by NASA and the Hyperion Project as impediments to matter/anti-matter propulsion had been overcome, at least in the laboratory. Based on these discoveries, the feasibility of matter/anti-matter propulsion for generating relativistic speeds in space was hypothesized, along with concepts for systems that could utilize Chen's and Stenson's discoveries to make matter/anti-matter propulsion practicable [17, 18].

6. Components of a matter/anti-matter spacecraft

Based on the discoveries of Chen and Stenson, the basic components of a matter/anti-matter propulsion system are fairly simple. The system will probably need four main components: a power source, a paired-particle generator, a storage system, and an annihilation chamber (or, an "interaction" chamber). Depending on the efficiency of the paired-particle generator, and the nature of the mission, it may not be necessary to have a storage system.

With a storage system, the engine would probably be ordered something like **Figure 7**, with a payload on top.

6.1 Power source

The power source for the system is probably going to be a fission-based nuclear reactor. These reactors have been used in industry and in multiple navies around the world. The reactor for space travel would be similar to the nuclear reactors used to power modern nuclear submarines. In the 1960s, nuclear reactors for propulsion systems for aircraft were developed in the United States, showing that the weight of a reactor required for a space-propulsion system should not be an impediment to success.

6.2 Paired-particle generator

The heart of the system is the paired-particle generator. Based on the work of Chen and her team, this component would require a high-energy laser and a gold (or similar) target substrate. It would also require a magnetic collection system. The magnetic system would collect the electrons and positrons generated by the laser and direct them to the storage component.

6.3 Storage system

The storage system will probably consist of twin tokamaks, one for storing electrons and one for storing positrons. A tokamak is a large magnetic container. It is shaped like a donut, and the magnets inside are also shaped like donuts. **Figure 8** shows the basic configuration of a tokamak; the electrons or positrons would be stored as "Plasma current".

The tokamaks for a matter/anti-matter propulsion system will probably be different from the fusion tokamaks that have been produced to date. Fusion tokamaks are designed to contain very high pressures. The tokamaks for matter/anti-matter space propulsion will probably not require such high pressures, but will still require creating very high magnetic forces.

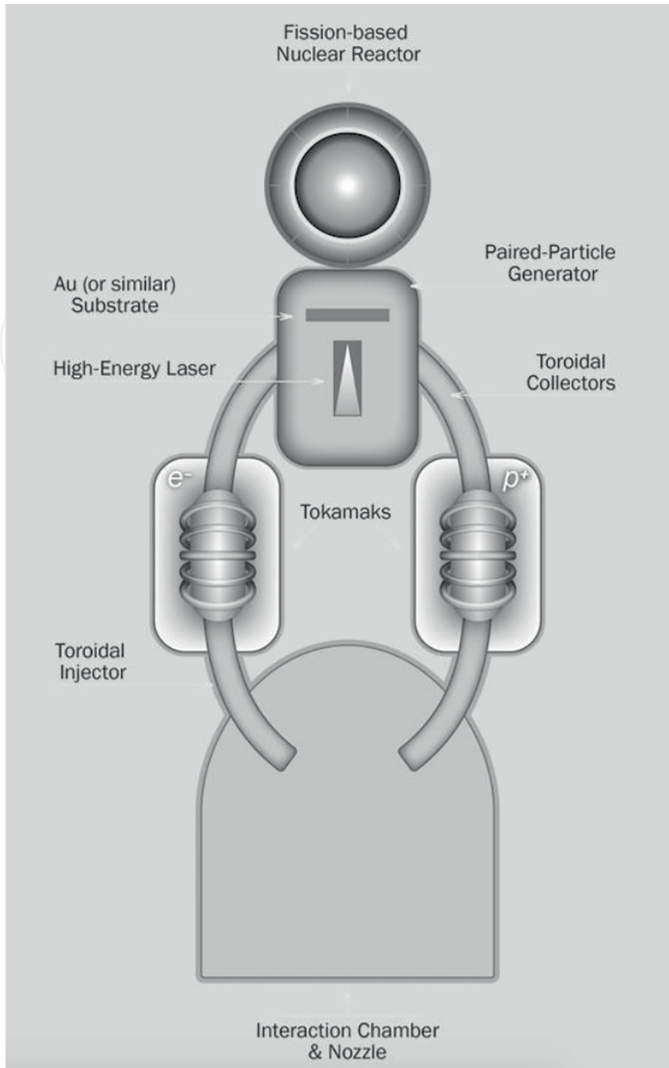

Figure 7.
System concept (courtesy Mustang Publishing).

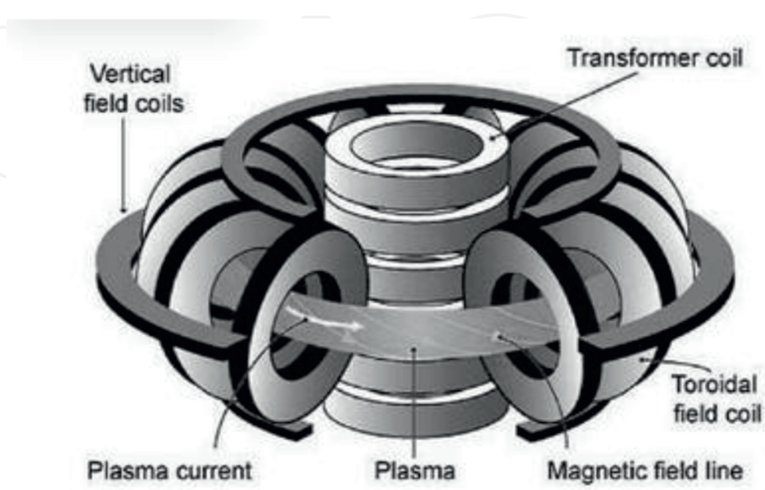

Figure 8.
Tokamak (courtesy Mustang Publishing).

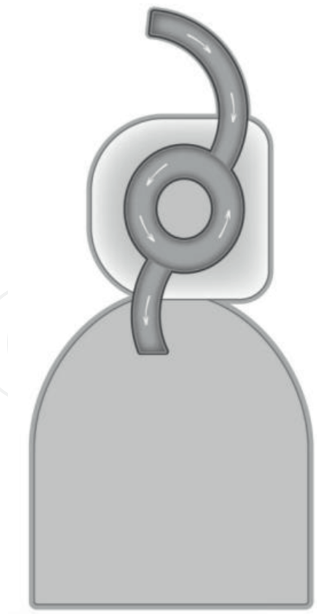

Figure 9.
Particle-flow diagram (courtesy Mustang Publishing).

Like the paired-particle generator, the twin tokamaks will require a magnetic system for directing the electrons and positrons to the annihilation chamber. In **Figure 7**, those components are called toroidal injectors.

The paired particles would flow into, and out of, the tokamaks in a pattern that is something like what is shown in **Figure 9**, with the tokamak "donut" in the middle:

6.4 Annihilation chamber

The annihilation chamber (or the "interaction chamber" in **Figures 7** and **9**) is where the electrons and positrons will collide and annihilate. It is where the gamma rays will be produced to propel the entire spaceship.

The annihilation chamber will, at least on its inside, be somewhat bell-shaped, although probably flatter. The shape is similar to the rocket nozzles that are used on chemical rockets. **Figure 10** highlights a cutaway of the interaction chamber, where matter/anti-matter annihilation will take place.

6.5 Interstellar probes

Probes to nearby stars will probably not require a storage system. Instead, the electrons and positrons created in the generator will probably be directed immediately to the annihilation chamber, where they will annihilate and propel the craft. The highest speeds are achievable when a mission, like an unmanned interstellar mission, has a low spacecraft weight and an extended time to travel.

The annihilation chamber will also be the probes' primary tool of stearing. In order to stay on target, moveable panels in the annihilation chamber will likely asymmetrically direct the gamma-ray "exhaust" to stear the probe.

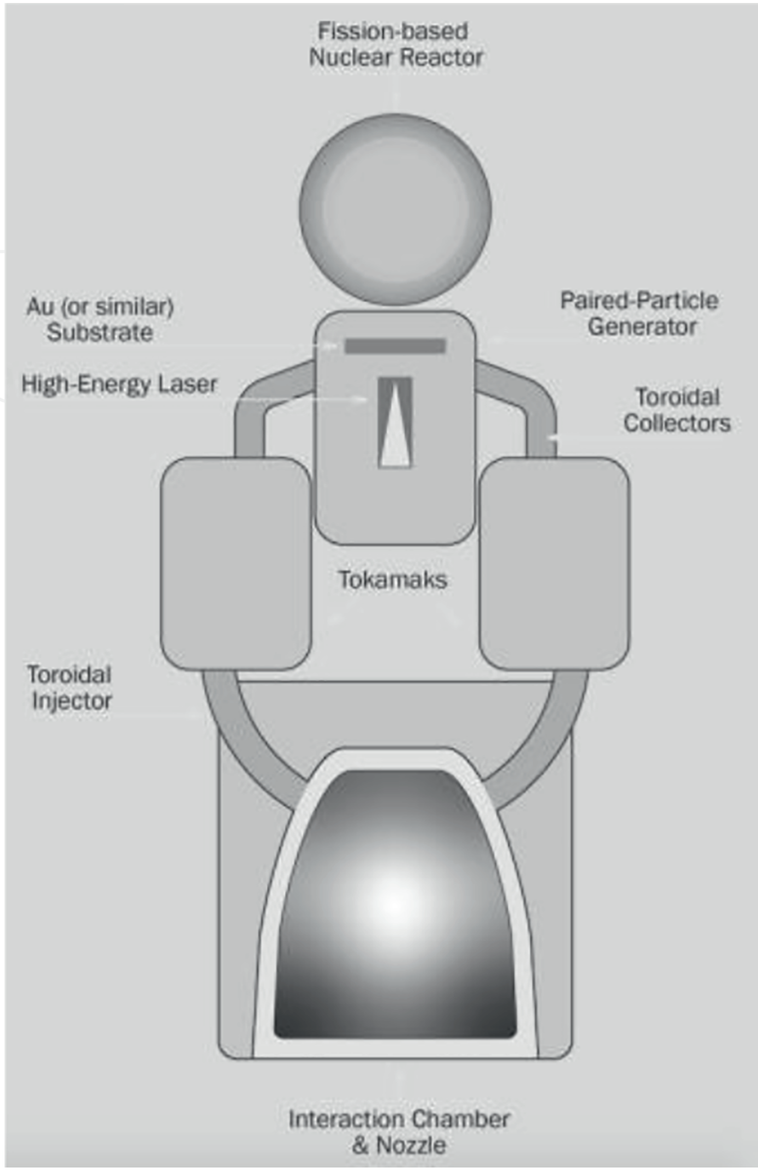

Figure 10.
Cutaway of annihilation chamber, or "interaction chamber" (courtesy Mustang Publishing).

6.6 Launch environment

The best launch environment for matter/anti-matter spacecraft is probably the Moon. With no atmosphere, the matter/anti-matter annihilations will be better controlled. The lower mass of the Moon permits faster launch acceleration. Furthermore, it is likely that chemical booster rockets will aid the initial launch of a matter/anti-matter spacecraft, in order to achieve maximum initial acceleration, somewhat like the solid-propellant rocket boosters of the United States' Space Shuttle and Artemis rocket. The United States' current Artemis Project would be well-suited to build the infrastructure and to ferry the components and materials for launch of an interstellar probe.

7. Theoretical speeds

It is possible to theorize the speeds capable of being achieved by matter/anti-matter-propelled spacecraft, based upon some reasonable assumptions involving the mass of the spacecraft and the production of paired particles by the system.

1. Some givens & approximations: (1) the hypothetical spacecraft weighs 10,000 kg; (2) an electron/positron annihilation produces 2 511-keV gamma rays; (3) the average Compton Effect force of a 511-keV gamma ray hitting an atom is approximately 200 keV [19]; (4) in the annihilation chamber, only about half of the gamma rays produced will strike the walls of the chamber, propelling the spacecraft; and (5) 100 keV = 1.6×10^{-14} N m; 100 keV = 1.6×10^{-14} kg m/s/s; 200 keV = 3.2×10^{-14} kg m/s/s.

2. Assuming that a paired-particle generator produces 6×10^{17} paired particles per second [20] (therefore producing approximately 6×10^{17} 511-keV gamma rays that will strike the annihilation chamber to propel the spacecraft, at an average of 200 keV per gamma ray), the force generated by the system is: $6 \times 10^{17} \bullet 3.2 \times 10^{-14}$ kg m/s/s $\approx 1.9 \times 10^{4}$ kg m/s/s.

3. Because the spacecraft, in this thought experiment, weighs 10,000 kg, and

$$F = ma\left(\text{Newton's Second Law}\right) \tag{2}$$

and

$$a = F / m, \tag{3}$$

The spacecraft will accelerate at approximately 1.9 m/s/s.

4. The formula for the velocity achieved by a constantly-accelerating object, starting at rest, is

$$v_f = at, \tag{4}$$

where, for our purposes, by international convention, velocity (final) is measured in meters/second (direction is not relevant for this purpose), acceleration is measured by meters/second/second, and time is measured in seconds.

5. Because there are 31,536,000 seconds in a year, the speed achieved by the spacecraft hypothesized here, after 1 year, would be approximately 6×10^{7} m/s. Because the speed of light (c) is approximately 3×10^{8} m/s, the spacecraft would, after 1 year, be traveling at approximately 20% of the speed of light. After 2 years of constant acceleration, the spacecraft would be traveling at approximately 40% of the speed of light.

Mission planning would necessitate sufficient time for deceleration, but these speeds, if achievable, indicate that relativistic speeds—speeds even approaching the speed of light—are conceivable with matter/anti-matter propulsion.

8. Validation testing

Just like Tsiolkovky's equation has significance for the practical limitations of chemical rockets, the velocity equation (Eq. (4)) has great significance for the possibilities of matter/anti-matter spacecraft. Because the speeds that can be achieved by a matter/anti-matter spacecraft are a function of the number of electron/positron pairs that can be produced, experimental determination of an optimized paired-particle generator's capacity to produce paired particles is the most logical first experimental step (in engineering terms, a "validation" step). These experiments, and follow-on experiments, should also determine whether the target substrate or the laser used are lost in some way ("burning", degradation of some sort, etc.) in the Bethe-Heitler Process, so that the potential *time* that the system can reliably operate can also be determined.

The first planned experiment to further develop this technology is an experiment to determine the specific numbers of paired particles that can be generated by a high-energy laser striking various targets. Taking advantage of a matter/anti-matter "circuit" in a custom laboratory apparatus, as well as a precision gamma-counting system designed for the task, Albireo Scientific Corporation is currently in the process of conducting this experiment, possibly under the auspices of the LaserNetUS consortium in the United States.

With this experiment, and follow-on experiments, it should be possible to determine the practical feasibility of matter/anti-matter propulsion.

9. Implications

It is reasonable to believe, based on Hui Chen's and Eve Stenson's laboratory discoveries, that matter/anti-matter propulsion is a viable—possibly the most viable—technology for achieving relativistic speeds in space. Instead of being mere science fiction, relativistic speeds are now defensible scientific theory, and they may, within a matter of a few years, become actual scientific and engineering fact.

With matter/anti-matter propulsion, the outer planets of our solar system are likely within our reach, for further scientific exploration. Most importantly, the nearest 15 stars to Earth are four to eleven light-years away [21]. At those distances, sending matter/anti-matter probes to our nearest neighboring stars, and receiving signals back from our probes, will involve a mission of only a few years. Possibly of greatest importance of all, two of the stars that are closest to us are a lot like our Sun. It would be intriguing, and potentially quite important, to find out how similar those two star systems are to our own.

10. Conclusion

When high-energy photons strike a nucleus, pairs of electrons and positrons are created. Those pairs can be separated and stored, or simply separated and re-directed, to a thruster where they can collide, annihilate, and generate 511-keV gamma rays. Those gamma rays can then strike the interior shell of the thruster and generate thrust via the Compton Effect. Depending upon the number of electron/positron pairs that can be generated in an optimized system, it is highly likely that relativistic speeds can be achieved by matter/anti-matter propulsion. The logical next step for developing this technology is a well-designed set of validation experiments. If matter/anti-matter propulsion is validated, probes to the nearest stars can be developed and launched, and their signals received, within a single human lifetime. The prospect of human interstellar travel using matter/anti-matter propulsion is now realistic and amazing.

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Any errors or failures here are solely the responsibility of the author.

Potential conflict of interest disclosure

The author is President of Albireo Scientific Corporation, an America corporation established to further experimental testing of matter/anti-matter propulsion.

Note

Although not directly related to the idea of matter/anti-matter propulsion, an outgrowth of this inquiry has been a novel, fundamental idea about the nature of matter and anti-matter in the Universe. In describing, and questioning, the composition of matter and anti-matter for this project, the author has hypothesized that what we understand as "matter" is actually a combination of quarks, anti-quarks, electrons, and positrons [22]. In other words, it appears possible that there is not a bifurcated distinction between all matter and all anti-matter. The initial validation experiment described here should help assess this hypothesis, in addition to helping develop matter/anti-matter space propulsion.

Regardless of the outcome of the fundamental physics inquiry pursued in this initial experiment, the prospects for matter/anti-matter propulsion will remain promising. In addition, better understanding of the components and energies within atomic nuclei may inspire technologies for space propulsion that will prove to be superior to matter/anti-matter propulsion.

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