Project Icarus

M6: Primary Propulsion

Could Antimatter be Generated and Stored in Sufficient Quantities to Assist with an Interstellar Mission?

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Abstract

Antimatter offers the highest possible energy density of any known substance, 90MJ/μg, upon annihilating its matter counterpart, making it ideal for power creation and propulsion for interstellar missions. For propulsion, proton-antiproton annihilation is preferred over electron-positron annihilation because the products of the reaction are charged particles that can be both confined and channeled axially for thrust by using magnetic nozzles. In contrast to this, electron-positron annihilation produces only high-energy gamma rays, which can neither be directed for thrust nor couple effectively to any working fluid to generate the desired propulsion. Antiproton production is currently not optimized, and therefore is both expensive and rare. The annual global production rate for antiprotons is on the order of 10 nanograms per year. In addition, a much lower number of antiprotons have been cooled, collected and stored. Thus, although antimatter initially appears to be an attractive option for Project Icarus for power and propulsion, the technical challenges associated with creating and storing antimatter in useful amount, may make it prohibitive, and it may not be considered a "credible extrapolation" of existing technology. In this paper we examine the state-of the art in antimatter storage and creation, and explore what we may expect in the future.

This is a submission of the Project Icarus Study Group.

Keywords: antiprotons, antimatter, Project Icarus.

Contents

1 Introduction

When subatomic particles annihilate with their antimatter counterpart, vast amounts of energy are released. As an example, the energy released from proton-antiproton annihilation is 10^{10} times greater than oxygen-hydrogen combustion, and is even 100 times more energetic than either fusion or fission. For comparison with conventional launch systems, a single gram of antihydrogen, when annihilated with a gram of hydrogen, produces an amount of energy equivalent to that delivered by 23 Space Shuttle External Tanks.

Eugene Sanger was the first to propose the use of electron-positron annihilation for propulsion [1]. The 'Sanger Photon Rocket' would utilize the gamma rays produced from the annihilation, which would be reflected axially rearward to generate thrust.

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The conventional techniques that are employed to create and trap antiparticles are incredibly inefficient since they rely on extracting antiparticles from sub-atomic collision debris in particle accelerators. The global production rate is currently in the nanograms range annually, at an estimated cost of about $100 trillion per gram. In addition, the antiparticles are difficult to control, since they annihilate on contact with normal matter. The antiparticles must be stored in a high vacuum environment and levitated in magnetic, electric and/or RF fields to avoid their annihilation upon contact with the container that's holding them.

The single key technology that is required to enable the revolutionary concept of antimatter propulsion is safe, reliable, high-density storage. [2]

According to Schmidt *et al* [3], two misconceptions regarding antimatter production have lead to skepticism regarding the practicality of, and the common belief that, energy costs would be excessively high so as to ensure that antimatter would never be competitive with other propulsion technologies. These misconceptions are:

1. **Antimatter is too expensive to create in useful quantities.**
2. **Vast quantities of antimatter would be needed for propulsion.**

With regard to the first misconception regarding the cost of antimatter, it's important to note that enriched Uranium-235 and liquid hydrogen were both extremely expensive when they began to be used, however, once the production infrastructure was in place, the costs dropped dramatically. For the second misconception, consider that, for a 'pure' matter-antimatter annihilation propulsion system, large quantities of antimatter would be required, however, numerous antiproton-catalyzed fission/fusion *hybrid* concepts exists which require far less antimatter. Quantities sufficient for such schemes could be within the range of production for the currently existing facilities at CERN and FNAL (Fermilab) after minor upgrades are made.

For the purposes of this research, we will consider antimatter requirements in the context of two propulsion concepts [4]:

- Antimatter Catalyzed Micro-Fission/Fusion (ACMF) Rocket
- Antimatter Initiated Microfusion (AIM) Rocket

Alternative antimatter propulsion schemes exist, namely the solid core antiproton rocket, the gas core antiproton rocket, the plasma core antiproton rocket and the beamed core antiproton rocket. However, the Project Icarus Terms of Reference [5] require that we focus on schemes that involve fusion. We briefly explain the concept behind both propulsion schemes.

ACMF Rocket: A pellet of Deuterium-Tritium (DT) and Uranium-238 (U-238) is compressed using particle beams, and irradiated with a beam of antiprotons, which are absorbed by the U-238 and leads to hyper-neutronic fission. This process heats the DT core rapidly which ignites, and then expands to produce thrust. The performance of this concept is estimated to be $I_{sp} = 13{,}500$s [6].

AIM Rocket: In this process, an antiproton plasma, within a Penning trap, is compressed using electric and magnetic fields. While this compression is occurring, DT or Deuterium-Helium-3 (D-He3) droplets are injected into the plasma. The plasma is heated due to antiprotons annihilating with a fissile seed, and a magnetic nozzle directs the exhaust for thrust. The performance of this concept is estimated to be $I_{sp} = 67{,}000$ for the D-He3 fuel, and $I_{sp} = 61{,}000$ for the DT fuel [6].

Before we can address the main questions in this paper, namely can antimatter be generated and stored in sufficient quantities for an interstellar mission, we need to determine what is 'sufficient'. That is, do we need $\sim\mu$g or do we need tonnes, for example?

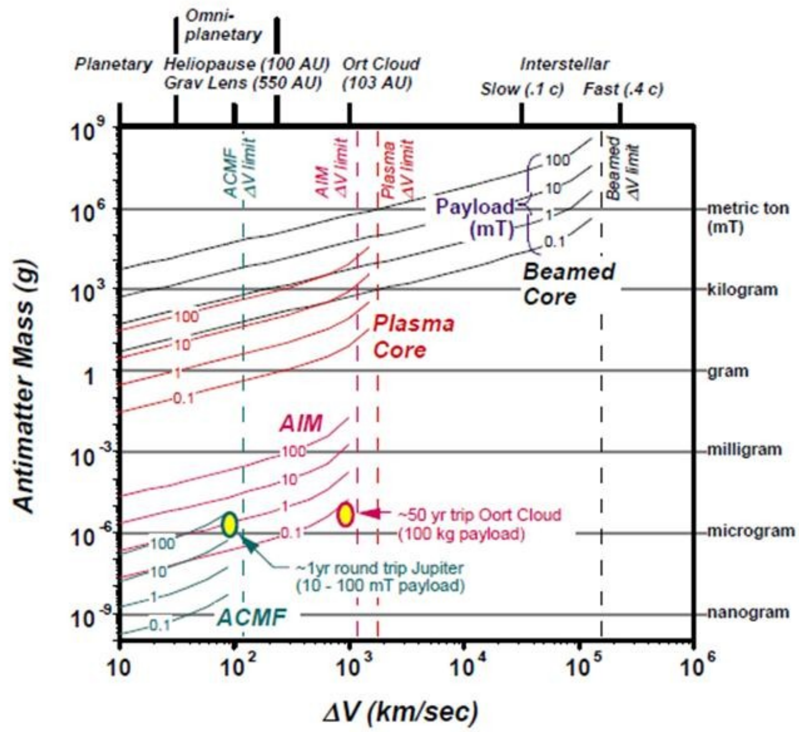

Figure 1. Antimatter mass requirement for range of propulsion concepts. Image courtesy [3].

Table 1. Both the ACMF and AIM concept utilize small amounts of antimatter to power the main fusion propulsion system. This table highlights some of the salient parameters from each system.

Propulsion Scheme	Mission Scenario	Specific Impulse (s)	Max ΔV	Fusion Gain	Payload Mass	Energy Utilization Efficiency, η	Amount of Antimatter
ACMF	Manned Jupiter	13,500	~100 km/s	1.60 E7	100 tonnes	15%	~10μg
AIM (D-He3)	Interstellar Precursor	67,000	~1,000 km/s	1.00E+05	100 Kg	84%	~100μg
AIM (D-T)	Interstellar Precursor	61,000	~1,000 km/s	2.20E+04	100 Kg	69%	~100μg

For the two schemes in which antimatter is used to initiate a fusion reaction, the antimatter requirements are quite low, on the order of 10-100μg. However, neither concept is suited to an interstellar mission that fits the Project Icarus Terms of Reference - specifically that the spacecraft must reach the target system in less than a century. This can be seen from the Δv range in Figure 1, where even the faster of the two concepts, AIM has a maximum Δv of ~.3%c, and so would take ~2000 years to reach the closest star.

There are alternative concepts, also shown in Figure 1. The beamed core antimatter rocket, for example, has a Δv range that would allow for extremely rapid interstellar transit, however, this is purely an antimatter propulsion scheme, with no fusion element - therefore again would fail to be consistent with the Project Icarus Terms of Reference requirement that the main propulsion system be fusion based.

One simple solution presents itself, that is, to simply use more fuel on either the ACMF or AIM concepts, however, the fuel to mass ratio's become prohibitive (~hundreds of millions to one).

Kammash [7] has explored the possible utility of antiproton driven magnetically insulated inertial confinement fusion propulsion (MICF) as part of a NIAC study. In his study, a 47 year flyby mission to the outer Oort cloud (~10,000 AU) with a vehicle of dry mass 220 tonnes, would require 166 g of antiprotons. Keeping in mind that the closest solar system to Earth is ~300,000 AU, we're starting to see that quite large quantities of antimatter are likely to be needed.

The author is not aware of any dedicated papers exploring an interstellar mission that involves antiproton drivers for fusion, thus, no numbers on readily available for the mass of antiprotons needed. We can, however, estimate the amount needed using the formula given in Schmidt [3].

The mass of antimatter required for a mission is found by using an equation derived by equating the applied annihilation energy to the kinetic energy of the exhaust, while accounting for the contribution of the fusion gain

$$M_a = \frac{1}{2(1+\beta)}\left(\frac{\gamma - 1}{\gamma + (\eta_e - 1)}\right)\left(\frac{R-1}{1+\lambda+R\lambda}\right), \tag{1}$$

where R is the relativistic mass fraction:

$$R = \left(\frac{1+\frac{\Delta v}{c}}{1-\frac{\Delta v}{c}}\right)^{\frac{2}{2v_e}}, \tag{2}$$

and γ is the Lorentz contraction:

$$\gamma = \frac{1}{\sqrt{1-\left(\frac{v_e}{c}\right)^2}} \tag{3}$$

also, M_a is the mass of antimatter required, η_e is the energy utilization efficiency, β the fusion power gain, and λ the vehicle dry mass to propellant mass ratio.

The following values were used to obtain the mass of antimatter required [3]:

Table 2. Parameters used for the AIM concept.

Parameter	Value
β	1.00E+05
η	0.840
Ve	6.70E+05
γ	1.00000499
Mpay	100000
c	3.00E+08

the values obtained were based on the AIM (D-He3) propulsion concept, with a test payload of 100 tonnes [3]. The results are shown in Figure 2 below.

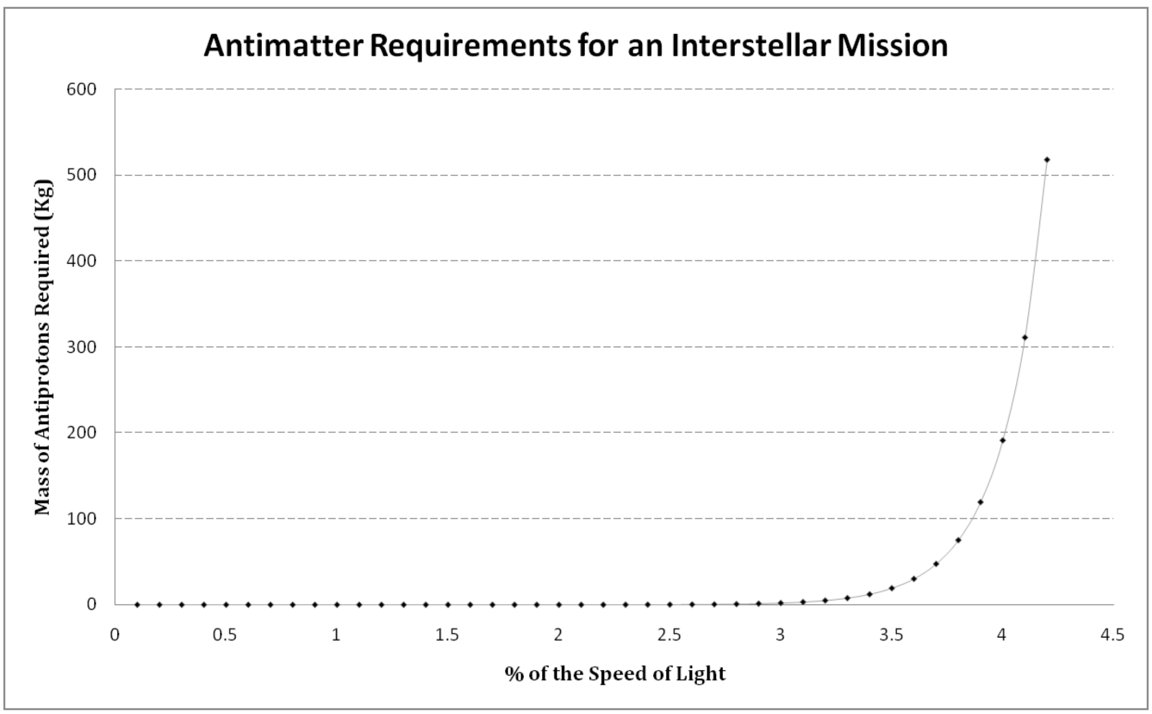

Figure 2. Mass of antiprotons required for the AIM propulsion concept. To reach the minimum necessary speeds to reach the closest star, within 100 years, ~100's of Kg of antimatter would be required.

Before we discuss the result obtained, it's worth recalling that the AIM concept was specifically designed for rapid *interplanetary* transit. Only ~10μg of antiprotons would be required to obtain a top speed ~1000 km/s with a vehicle dry mass to propellant mass ratio 0.1. However, a Δv limit is rapidly reached with this value of λ. In fact, a range of λ where explored for this paper, and, to obtain a top speed of 4.2%c (the minimum speed required to reach the closest solar system within the 100 limit of the Project Icarus Terms of Reference) it was discovered that one would need:

$$\lambda = 1 \times 10^{-9} \tag{4}$$

and

$$M_a = 518 \text{ Kg.} \tag{5}$$

This mass ratio λ is unrealistic. Essentially, one would need approximately one billion tonnes of fusion fuel, for every tonne of payload. This seem prohibitive and would not likely be implemented. In addition, the mass of antimatter required for this $\sim 10^{14}$ times current production rates. This appears to be too great an extrapolation of technology to be taken seriously.

Upon researching the possible use of antimatter to initiate fusion reactions, it appears that most of the schemes that have been studied, to date, are optimized for rapid interplanetary transit, and that there are no designs (to the authors current knowledge) that are optimized for rapid interstellar transit. Indeed, in studying the AIM concept further, it became apparent that for approximately every 0.5%c increase in Δv, that an order of magnitude mass ratio was introduced. This is summarized in the table below.

Table 3. Vehicle dry mass to propellant mass ratio for the AIM propulsion concept.

Mass Ratio	Top Speed (%c)
1	0.1
1.00E-01	0.5
1.00E-02	1
1.00E-03	1.5
1.00E-04	2
1.00E-05	2.5
1.00E-06	3
1.00E-07	3.5
1.00E-08	4
1.00E-09	4.5

Because of this, the basic questions posed in this trade study, namely can we generate and store sufficient antimatter necessary for an interstellar mission, needs to be preceded by a more fundamental question, namely:

'What is the minimum amount of antimatter that would be necessary to ignite fusion reactions for a fusion powered spacecraft that would allow for a mission consistent with the Project Icarus Terms of Reference'.

- The first recommendation of this paper is to perform a Phase 4 study to determine the answer to the above question.

Although the answer to the question posed in the title of this study cannot be precisely answered at this stage, we can examine the current state-of-the-art.

2 Fundamental Concepts

Antimatter for propulsion purposes is usually assumed to be in the form of antiprotons, neutral antihydrogen, or anti-molecular hydrogen. Antimatter has long been known to be an extremely efficient propulsion fuel due to the fact that its specific energy is the highest when compared to all other fuels. However, the ability to store antimatter in large quantities has always been an issue.

The annihilation of antiprotons is a strong interaction process that takes place at the level of the quark structure of the nucleus. The proton is composed of a pair of "up" quarks, each having a charge of +2/3, and a single down quark with charge -1/3. The antiproton, being the mirror particle of the proton contains two anti-up quarks each with a charge of -2/3, and one anti-down quark with charge +1/3. When an antiproton annihilates with an isolated proton, at rest, 1.88GeV of annihilation energy is generated. This energy is translated into the kinetic energy of charged and neutral pions and their rest mass, with an energy division of ~64% and ~36% respectively. In approximately 5% of the annihilation events, a kaon pair is emitted, which rapidly decay into neutrinos, positrons and electrons. The positrons ultimately annihilate with the surrounding medium, creating gamma rays. [8].

3 Technological Maturity

3.1 Production

Most of the antimatter produced globally is made either at CERN or Fermilab. In the late 90s, Fermilab was producing 1ng of antiprotons. The instantaneous production rates were 10^{11} antiprotons per hour, therefore a year of dedicated production would have created 8.8×10^{14} antiprotons, or an annual yield of about 1.5 ng. This is roughly 3-4 orders of magnitude lower than is necessary for the AIM or ACMF concepts. It's important to note, that neither CERN or Fermilab are specially dedicated facilities focused on producing antimatter, and therefore the production rates could very easily be dramatically increased.

3.2 Storage

Experiments in the storage of antimatter has been ongoing over the past few decades. Typically a Penning trap is used. These devices store charged particles using a combination of magnetic and electric fields. In the late 90s, the PS200 experiment stored [9] 10^6 antiprotons for several hours. Penning traps will have an ultimate limit, however, based on the space charge density. Another, more attractive, option is to store the antiprotons in the form of neutral antihydrogen. Recently [10] physicists working at CERN's Antihydrogen Laser Physics Apparatus trapped 309 antihydrogen atoms for 1000 seconds. Currently the most advanced antiproton portable trap is the HiPat which has the capacity to hold 10^{12} antiprotons – or roughly 1 picogram, for several days.

4 Future Advances

It has been suggested by Hora [11] and Crowe [12] that high intensity lasers could produce antimatter. One of the key elements to making this concept work is the efficient generation of laser pulses with sufficient energy.

Lapointe [13] has suggested that the Casimir Force be used to generate steep energy gradients that could create antiprotons at a potential barrier. The approach has not yet been demonstrated, however the physics could be validated with positrons with less experimental challenge associated with it. A number of condensed matter ideas also exist, including utilizing photon band-gap structures, quantum reflection and paraelectricity .

In a recent NIAC Phase 1 study Bickford [14] has described a natural antiproton radiation belt analogous to Earths Van Allen belts, which currently surrounds the Earth. In addition, cosmic radiation interacting with the upper atmosphere also generates antiparticles from pair production.

Bickford estimates that Earth has a trapped supply of 160ng, with a replenishment rate of 2ng/yr. Saturn is believed to have the maximum trapped antiprotons compared to all other planets in the solar system, with 10μg stored, and a replenishment rate of 240μ/yr. He also proposes numerous collection methods that range from collectors with a mass of 10^4 Kg, and collection rate of 10^{-11}ng per year, up to $\sim 10^{10}$kg and a collection rate of up to .1ng per year. Given the relatively low rates production capabilities of this scheme, and early indications from this paper that ~μg will be too little for our needs, this scheme does not appear initially appealing.

5 Conclusions

Early results from this paper indicate that fusion propulsion utilizing antimatter as the driver, may not be an effective propulsion scheme for interstellar missions, based on the performance of the AIM and ACMF. Even under the most optimistic scenario of visiting the closest star in 100 years, and that ~hundreds of Kg of antimatter may be required. However, it is possible that these propulsion schemes, optimized in performance for rapid interplanetary missions, may not be the best use of antimatter for our requirements.

6 Recommendations

Early results from this paper indicate that fusion/antiproton hybrid propulsion systems may not deliver the performance necessary to fulfill the Project Icarus ToR. However, before this scheme is ruled out, it is recommended that a Phase 4 study be performed to determine if more effective fusion/antimatter propulsion schemes can be designed, that could fulfill our ToR, while keeping antimatter requirements down to more realistic levels (~10's-100's of μg).

Once a clearer picture of the antimatter requirements are determined, then an investigation into the storage and production can be more effectively undertaken.

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