# Viable Propulsion Methods for Interstellar Travel

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**This paper outlines the history and future of viable interstellar propulsion systems. For context, conventional rocket propulsion systems including chemical and fission powered systems are explored for use in interstellar travel. We see that these systems are unsatisfactory due to generally low specific impulse numbers. As an alternative, fusion and antimatter powered systems are suggested due to their exceptionally high energy density and thus high specific impulse allowing for a long but reasonable mission time.**

## I. Nomenclature

| | | |
|---|---|---|
| $v$ | = | velocity of vehicle |
| $v_e$ | = | effective exhaust velocity |
| $m_0$ | = | vehicle initial mass |
| $m_f$ | = | vehicle final mass |
| $I_{sp}$ | = | specific impulse |
| $T$ | = | thrust |
| $W$ | = | weight of vehicle (on Earth) |
| $\dot{m}$ | = | mass flow rate |
| $m$ | = | mass of body in motion |
| $a$ | = | acceleration of body in motion |
| $g$ | = | gravitational acceleration, $9.8\frac{m}{s^2}$ |
| $\Delta t_{obs}$ | = | moving observer's period of clock |
| $\Delta t_{rest}$ | = | resting observer's period of clock |
| $v_{obs}$ | = | velocity of moving observer |
| $c$ | = | speed of light, $3 \times 10^8 \frac{m}{s}$ |
| $m_p$ | = | mass of a proton, $1.67 \times 10^{-27}$ kg |

## II. Introduction

This paper discusses viable propulsion systems for use in interstellar travel. Propulsion aims to solve a fundamental human dilemma: transportation, or the controlled spatial relocation of mass. With that being said, the universe is in a constant state of entropy increase; in order to move something across space you will have to put in extraordinary amounts of energy to ultimately make that relocation temporally efficient and entropically favorable for the universe.

To explain this energy requirement, we can look to basic Newtonian mechanics. In order to change the location of anything, a force must be applied. Conventional rocket propulsion systems leverage Newton's third law [1], for every action there is an equal and opposite reaction, by expelling mass to create thrust. Using these fundamental principles, in the early 1900s Tsiolkovsky's rocket equation [2] was derived:

$$\Delta v = v_e \ln(\frac{m_0}{m_f}) \tag{1}$$

This equation is critical to the understanding of modern rocket propulsion since alternative forms of force generation have been unsuccessful. With that being said, highly theoretical propulsion systems may leverage the fundamental forces of gravity to create propulsion forces, though this would require the ability to manipulate gravity and is escaping the scope of this project *. Nonetheless, modern rocketry operates on the seemingly wasteful principle that some significant

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*Though current technologies don't allow us to spontaneously use gravity in a propulsion system, gravity has certainly been used to increase vehicle velocity as known in orbital mechanics as a gravity assist.

percentage of vehicle mass will be allocated to thrust generation. Modern propulsion systems like the Falcon 9 must use a staggering 540,000 kg of thrust generating mass to place only 8,300 kg of payload into high altitude orbits [3].

### A. Metrics Governing Propulsion

To discuss propulsion effectively, an introduction into some metrics governing the performance of propulsion systems is warranted. The first and likely most important in the context of interstellar travel is specific impulse.

$$I_{sp} = \frac{T}{\dot{m}g} = \frac{v_e}{g} \tag{2}$$

With units of seconds, specific impulse is ubiquitously considered as the metric to use to assess propulsive capabilities since it effectively measures thrust production for a given usage of propellant mass. For a relatively inefficient rocket motor like Apollo 11's F-1 main rocket engine, we can achieve specific impulses of around 260 seconds. Alternative propulsive devices like ion thrusters can achieve specific impulses well above 1000 seconds [4] [5], offering exciting energy driven alternatives to chemical propellants.

With that being said, while specific impulse is important, a myriad of high specific impulse motors generate thrust efficiently but far too slowly (like the aforementioned ion thrusters [4]). Due to the vast distances between interstellar objects, to maintain a feasible timescale we must considers engines capable of producing a high specific impulse but that can also do so relatively rapidly. While some interstellar travel methods have been proposed to increase mission duration past that of a human life by using a 'generation' ship [6], or a ship which is able to sustain multiple generations of human life during travel, due to concerns described in the section below a large effort has been made to make interstellar propulsion systems with mission times less than that of a human life. Two factors thus go into play when considering how effective a propulsion system is at creating realistic, sub-human-lifetime mission times.

The first is another quantitative metric which serves to measure vehicle acceleration capabilities. The thrust to weight ratio for a propulsion system measures exactly what it describes, the thrust to weight ratio [7].

$$\frac{T}{W} = \frac{ma}{mg} = \frac{a}{g} \tag{3}$$

By expanding these terms out using basic Newtonian mechanics, we can see the thrust to weight ratio accurately describes vehicle acceleration normalized to Earth's gravitational acceleration. High thrust-to-weight ratios correlate to high vehicle acceleration possibilities, ultimately reducing transportation time. Propulsion systems which achieve a high thrust-to-weight ratio with a simultaneously high specific impulse will stand out as superb candidates for interstellar travel.

Secondly, and the final other factor to consider, to realistically accomplish faster than human lifetime travel we must[†] achieve exceptional travel speeds to take advantage of the speed-derived time dilation effects caused by Einstein's special relativity:

$$\Delta t_{obs} = \frac{\Delta t_{rest}}{\sqrt{1 - \frac{v_{obs}^2}{c^2}}} \tag{4}$$

By achieving high and nearly relativistic velocities we can leverage the relativistic properties demonstrated by Einstein to achieve realistic mission times. By constantly accelerating the aircraft from rest to $0.1c$ (10% of the speed of light), a one-way mission to the nearest stars is possible and would only relativistically take 40 years [8]. In an enlightening paper released by NASA, as seen in Figure 1 the only proposed propulsion devices capable of achieving this metric are fusion and antimatter technologies with solar sail technologies offering as a promising but less likely candidate.

### B. General Interstellar Travel Considerations

Though interstellar propulsion is largely limited by the average human lifetime, there are a variety of other ethical considerations which govern their overall usage. In general these are all related to the well-being of humanity. This section will provide a brief overview of some of these considerations before diving into the technical details of specific propulsion systems in later sections.

[†]Even at the speed of light and going to the closest star, Proxima Centauri, without time dilation the travel time will take at a minimum of 4.24 years. Achieving anywhere near these minimum numbers is wildly unrealistic, and mission time will thus only stand to increase greatly.

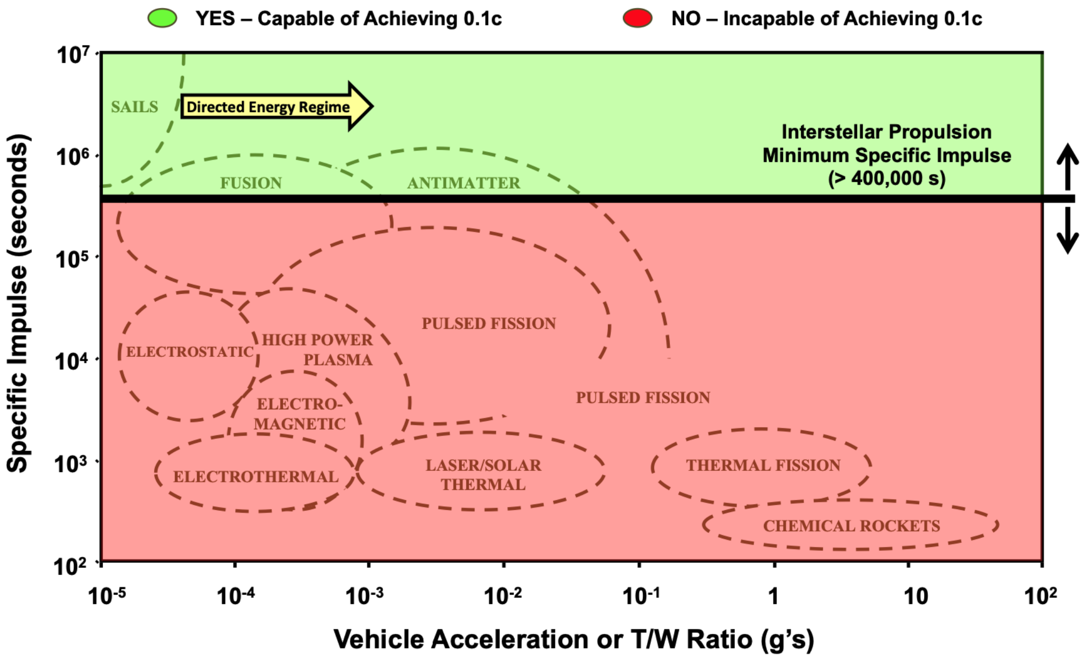


**Fig. 1 The viability of various known propulsion technologies characterized by specific impulse and achievable spacecraft acceleration**

*1. Radiation*

One of the most obvious changes made when shifting focus from interplanetary to interstellar travel is the harshness of interstellar media. Due to the atmosphere, Earth's magnetosphere, and the Sun's heliopause [9], humanity has constantly been shielded from DNA-destroying high energy particles which crowd the universe. By definition, interstellar travel will venture into areas without any solar protection. Of course, interstellar exploration is sufficiently far from the sun to avoid any comparable amount of solar radiation that was experienced by analogous interplanetary missions like the Apollo missions [10], though cosmic rays and other high energy particles pose serious dangers to astronaut livelihood. With that being said, radiation protection is a large unsolved problem in interstellar exploration. One of the only solutions we currently have for radiation protection is to simply add thick, high density shielding around the spacecraft.

Though this may offer radiation protection, this would detrimentally increase the mass required for safe interstellar travel, heavily constraining the possible propulsion systems used in interstellar craft. Additionally, over long periods of time, shielding has logarithmic benefits when it comes to radiation protection as seen in Figure 2. With that being said, [11] proposes that metals offer poor protection against radiation and that liquids or plastics may offer greater protection at a fraction of the weight.

*2. Ethics of Generation Ships*

The ethics surrounding interstellar travel are heavily debated, from child birth to insulated societies. To offer a brief discuss on the subject to contextual our discussion of interstellar propulsion, in order to successfully explore distances comparable to the radius of the Milky Way a generation ship is likely required due to the limits of baryonic velocity. Thus, the dynamics behind interstellar child birth and insulated societies must be considered.

In regards to child birth, the most important consideration is ethical; is it wrong to force our child to be born into the dreams of their ancestors? Of course, every human has their own interests and motivations, thus, how would we know that generations of interstellar humans would continue to share our goal for interstellar expansion? Yet, humans on Earth are much the same: our ship is merely planet sized. If a generation ship was massive enough to emulate the diversity of Earth life, interests across generations may be aligned. Again, this then fundamentally informs our investigation into viable interstellar propulsion systems. With that being said, apart from the ethical considerations that must be made we

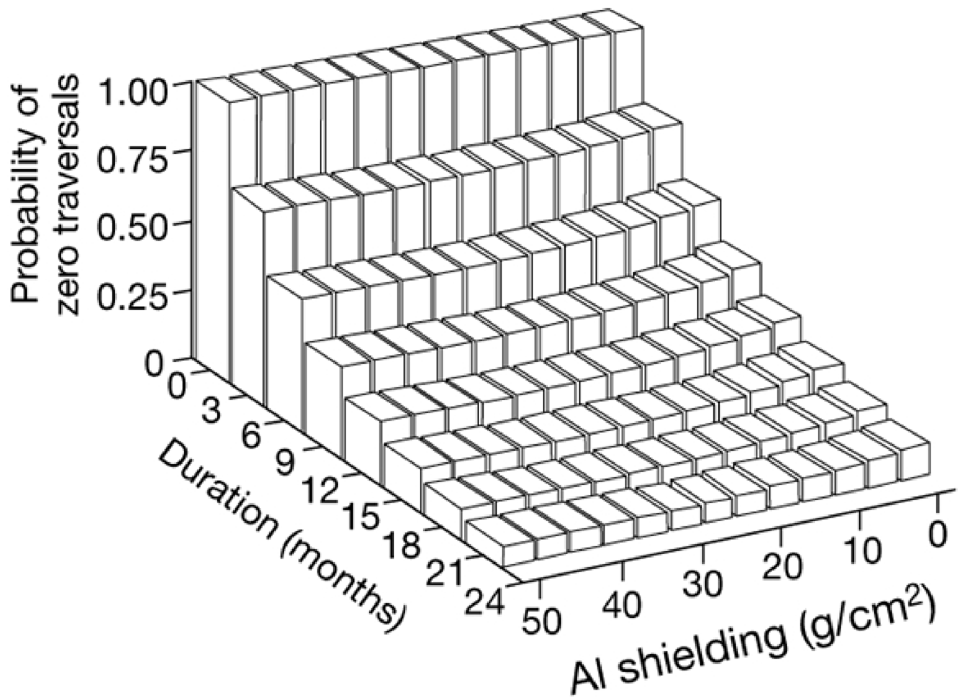


**Fig. 2 Radiation shielding by different aluminum densities over exposure time**

must recognize the biological complexity of child birth. From radiation caused defects to a lack of genetic diversity, creating a generation ship requires a fundamental understanding an manipulation of reproduction [12].

On the other, more speculative side of this, how does culture and society change across the generations when confined to a generation ship [12]? Is societal collapse too probable to even consider a generational ship? And if a society does sustain itself through the journey, what beliefs will remain compared to their ancestors? Looking introspectively at our past, cultural and ethical discussions vary widely between eras. Perhaps a generational ship isn't possible not because of technical limitations but because of cross generational incompatibility.

*3. Intersteller Travel Paradox*

The final interstellar travel consideration to make is seemingly a paradox though it is more of a technical limitation. Naturally, as explained in great detail above, we want to reduce the time required to complete an interstellar journey. With current life expectancy estimates, as explained in [8] we know realistic estimates place viable interstellar trips at around 40 years for observers on board the interstellar craft. However, for observers on Earth, their journey will still require a substantial amount of time. Considering the rate of progress in technology that we've seen over the past twenty years or even during the space race of the 60s and 70s, a significant improvement in technology may occur between the time an interstellar craft leaves and the proposed arrival time for that interstellar craft. If technology has improved sufficiently, it may be realistic to say that an interstellar craft leaving twenty years later (but with far superior propulsion systems) may arrive even sooner than the original interstellar craft. Thus, there exists some optimal 'exploration' time where future progress is so minimal or where current progress is so substantial that future interstellar craft don't simply catch up to your craft during transit.

## III. Current Propulsion Systems and Their Viability

### A. Chemical Propulsion

Throughout the entire history of rocketry, chemical rockets have dominated and still dominate the space due to their relatively obvious form of energy creation, straightforward and parallelizable testing, controllability, comparable manufacturing to car engines, and their broad range of potential implementations. When modern rocketry began in the early 20th century by Robert Goddard, liquid chemical rockets powered with gasoline and oxygen were used. This evolved throughout the space race to refined kerosene (RP-1), eventually being taken oven by LOX[‡] which will ultimately be taken over by liquid methane pioneered by SpaceX motors [13]. Be it liquid, hybrid, or solid rockets, such technologies are so ubiquitous in the field they are sometimes mistaken for accounting for the entire field. Yet, with all this history and with all of that being said, the bottom line is their mass to energy ratio is incredibly inefficient and thus unfit for interstellar space.

An inherent aspect to any rocket propulsion technology is the creation of energy. Looking back to equation (1), if we can expel mass at a higher velocity we will increase $v_e$ which will increase $\Delta v$, ultimately reducing mission time. By generating heat and pressure through chemical combustion, we can leverage the properties of supersonic gas through crafty engineering to increase the effective exhaust velocity. In a chemical rocket, this energy will come from the basic underlying chemistry of combustion for our decided reactants.

Combining equation (1) and equation (2), we see that:

$$\Delta v = g_0 I_{sp} \ln(\frac{m_0}{m_f}) \tag{5}$$

Leveraging this equation, we can calculate the maximal potential velocity increase for chemical rockets using the most efficient chemical rockets. Currently, the record for the most efficient liquid chemical rocket is held by a tripropellant system developed by Rocketdyne in the 60s consisting of a lithium, fluorine, and hydrogen mixture [14]. This engine achieved a maximum specific impulse of around 520 seconds. Knowing the minimum speed required to effectively transport humans on the scale of a lifetime to be $0.1c$, we can calculate the mass ratio required for a chemical rocket with this ideal engine to perform interstellar travel.

$$\Delta v = g_0 I_{sp} \ln(\frac{m_0}{m_f}) \tag{6}$$

$$0.1c = 9.8 * 520 \ln(\frac{m_0}{m_f}) \frac{m}{s} \tag{7}$$

$$\frac{0.1 * 3 \times 10^8}{9.8 * 520} = \ln(\frac{m_0}{m_f}) \tag{8}$$

$$\frac{m_0}{m_f} = 4.9 \times 10^{2556} \tag{9}$$

Even with this relatively trivial calculation, we can see the absolute absurdity of chemical rockets in an interstellar context. If we wanted a payload with the mass of a proton $m_p$, for this engine we would require a spacecraft of around $10^{2529}$ kg, roughly $10^{47}$ universes. This doesn't even take into consideration the logarithmic energy requirements required to reach relativistic speeds, showcasing just how impossible chemical propulsion is in this context.

### B. Fission Powered Propulsion

As an alternative to chemically powered flight, ionic propulsion has been widely adopted to propel low mass craft like satellites [15]. As opposed to generating energy through the combustion of chemical reactants, ionic propulsion derives its main energy input through electricity. By bombarding propellant with electrons we can ionize propellant atoms which will allow us to rapidly discharge them through electromagnetic interactions powered by electricity. In most cases, the propellant used is Xenon due its high molecular mass and easy storage parameters[§].

There are two main advantages to this system. Firstly, the electrical energy required can easily be extracted through local resources. In the case of interplanetary travel, the sun's energy is commonly utilized through solar panels to collect and convert solar radiation energy into electrical for propulsion. In the case of interstellar travel, since solar flux decreases exponentially as we move farther away, the dependence on the sun's resources becomes unrealistic. Nonetheless, we can avoid this by exploiting fission energy which is well explained by Figure 4.

As a second advantage, ionic thrusters have a high specific impulse as seen in Figure 3. By leveraging electromagnetic forces, ions can be propelled to unparalleled velocities [5] ultimately increasing specific impulse. Notice though their minuscule thrust characteristics (represented in micro Newtons). We will discuss the significance of this in later sections.

[‡]Liquid oxygen and liquid hydrogen.

[§]High molecular mass if favored because more mass can be expelled, ultimately meaning a higher change in momentum for our craft. Xenon is stored easily because it's a noble gas.

| Mission | Objective | Country | Launch | Orbit | Thruster | Propellant | Thrust (mN) | Isp (s) | Purpose |
|---|---|---|---|---|---|---|---|---|---|
| SERT-1 | Technology test | US | 1964 | Sub-orb | Ion | Hg<br>Cs | 28<br>5.6 | 4900<br>8050 | EP test |
| Zond-2 | Exploration | USSR | 1964 | Interplanet (Mars) | PPT | Teflon | 2 | 410 | EP test |
| Meteor 1-10 | Meteorology | USSR | 1971 | LEO | Hall | Xe | 20 | 800 | Orbit control |
| Intelsat V 2 | Communication | US | 1980 | GSO | Resistojet | Hydrazine | 0.45 | 300 | Station keeping |
| Telstar 401 | Communication | US | 1993 | GSO | Arcjet (MR-508) | Hydrazine | 250 | 500 | Station keeping |
| Deep Space 1 | Technology test | US | 1998 | Interplanet | Ion (NSTAR) | Xe | 20–90 | 3100 | EP test |
| Artemis | Communication | Europe and Japan | 2001 | GSO | Ion<br>RIT-10<br>Kaufman | Xe | <br>15<br>18 | 3370 | EP test, orbit raising |
| Smart-1 | Technology test | Europe | 2003 | Moon | Hall | Xe | 67 | 1540 | Main propulsion |
| Hayabusa-1 | Exploration | Japan | 2003 | Interplanet | ECR ion (4 μ10) | Xe | 8 | 3000 | Main propulsion |
| Dawn | Exploration | US | 2007 | Interplanet | Ion (3 NSTAR) | Xe | 90 | 3100 | Main propulsion |
| Goce | Earth observation | Europe | 2009 | LEO | Ion (2 T5) | Xe | 1–20 | 3000 | Air drag compensation |
| Hayabusa-2 | Exploration | Japan | 2014 | Interplanet | ECR ion (4 μ10) | Xe | 10 | 3000 | Main propulsion |
| LISA Pathfinder | Technology test | Europe | 2015 | L1 | Colloid | Cs | 0.0001–0.15 | 240 | Orbit and attitude control |
| BepiColombo | Exploration | Europe, Japan | 2018 | Interplanet (Mercury) | Ion (4 T6) | Xe | 145 | 4000 | Main propulsion |
| Uwe-4 | Technology test, nano sat | Germany, Russia | 2019 | LEO | FEEP | Ga | 0.001 | Several thousand | Orbit control |

**Fig. 3 Various missions equipped with ionic thrusters and the performance characteristics of said ionic thrusters**

Repeating the mass fraction calculation performed on chemical rockets for ionic powered rockets returns similar yet slightly more hopeful results.

$$\ln(\frac{m_0}{m_f}) = \frac{0.1 * 3 \times 10^8}{9.8 * 8050} \tag{10}$$

$$\frac{m_0}{m_f} = 1.42 \times 10^{165} \tag{11}$$

This is still wildly unreasonable, and is compounded by the fact that ionic thrusters have terrible thrust to weight ratios. Thus, not only would we require an unrealistically massive spacecraft to reach the desired speeds, all occupants on the spacecraft will be dead before arrival, showcasing how unfeasible ionic thrusters are as a valid interstellar propulsion technique.

## IV. Interstellar Propulsion Being Researched

### A. Fusion Propulsion

As a sibling to fission powered propulsion, fusion propulsion is an exciting potential solution to interstellar propulsion. Fundamentally, due to strong and weak interactions in atoms, each element has some associated binding energy which describes how much energy is required to separate the constituents of that atom as seen in Figure 4. In regards to fission, high mass nuclei are naturally unstable and may decay spontaneously, often giving off energy in the form of heat and radiation until its at one of the universes most stable nuclei: Iron-56. Thus, fission energy has become ubiquitous in every day life due to the seemingly non-existent conditions necessary to kick start energy generation; we're familiar with the energy provided by nuclear power plants and the massive energy release of atomic bombs. However, fission is the undesirable part of this conversation. Extremely low mass nuclei like Hydrogen isotopes and some Helium isotopes have an exceptionally low binding energy. By binding (fusing) these lower mass particles together, an enormous amount of energy can be retrieved as is currently being performed in the core of every burning star. Yet, as the context may insinuate, the requirements for fission to take place are volatile.

Currently, research is being conducted to simply construct any reliable form of fusion power generation [16]. An immediate application of fusion derived power is rather trivial; instead of using fission to power ionic thrusters use

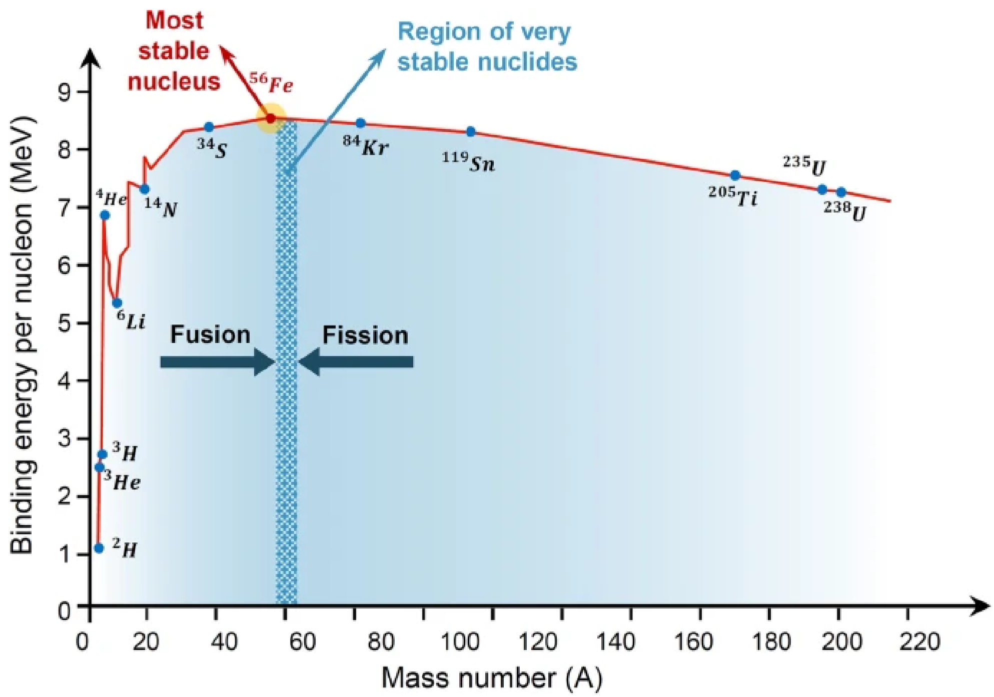


**Fig. 4 Binding Energy Versus Mass Number**

fusion! While that may seem promising, it is left to be seen if improved ionic thrusters can be constructed. On the other hand, instead of indirectly using fusion to power an electrical propulsion system, we can directly use the high energy processes related to fusion to provide thrust for our rocket. This system would involve a typical 'combustion' chamber which generates superheated plasma to effectively allow fusion to take place. While fusion takes place in the combustion chamber, a nozzle would be constructed to allow some percentage of fused charged particles to escape [17].

Such a technology would allow for exceptionally high specific impulses with estimates going above $10^5$ seconds. Of course, another advantage of these systems is the characteristically light atomic mass number used for fusion (and thus used as a propellant), ultimately meaning that an astonishingly high energy density for the propellant can be achieved in comparison to chemical rockets. For a crude comparison, a typical LOX reaction releases $1.35 \times 10^7 \frac{J}{kg}$ [18]. Assuming our fusion reaction converts/fuses hydrogen into helium and perfectly collects all of the released energy, we will have around 6 MeV for each four hydrogen atoms fused. Considering that there are 1000 times an Avogadro's number of atoms in a kilogram of material, each kilogram of hydrogen will contain $6.023 \times 10^{23} * 1000 = 6.023 \times 10^{26}$ hydrogen nuclei. This then gives us the astonishingly high energy release of $1.447 \times 10^{14} \frac{J}{kg}$ for the fusion of hydrogen, nearly exactly 10 million times the energy release of chemical rocket propellant.

Though these capabilities are ideal, having low propellant molecular mass means our thrust characteristics will be abysmal in comparison to the specific impulse characteristics of the engine. Yet, like an afterburner on a scramjet engine, we can improve thrust characteristics via the re-injection of hydrogen propellant which has been heated through regenerative cooling systems [17]. Finally, we can see that fusion driven propulsion becomes an effective option for realistic interstellar travel. Though, even though the physics allows these processes, massive engineering hurdles must be cleared to realize these dreams.

### B. Antimatter Annihilation Propulsion

In a similar vein to fusion propulsion, antimatter propulsion aims to find low mass particles with high energy potential characteristics which may lead to unprecedented energy release numbers. Fundamentally, antimatter annihilation propulsion consists of bringing two baryonic antiparticles into close proximity and allowing them to annihilate one another. Antimatter annihilation is a known mechanism underlying particle physics, though due to scope it won't be explored extensively in this paper.

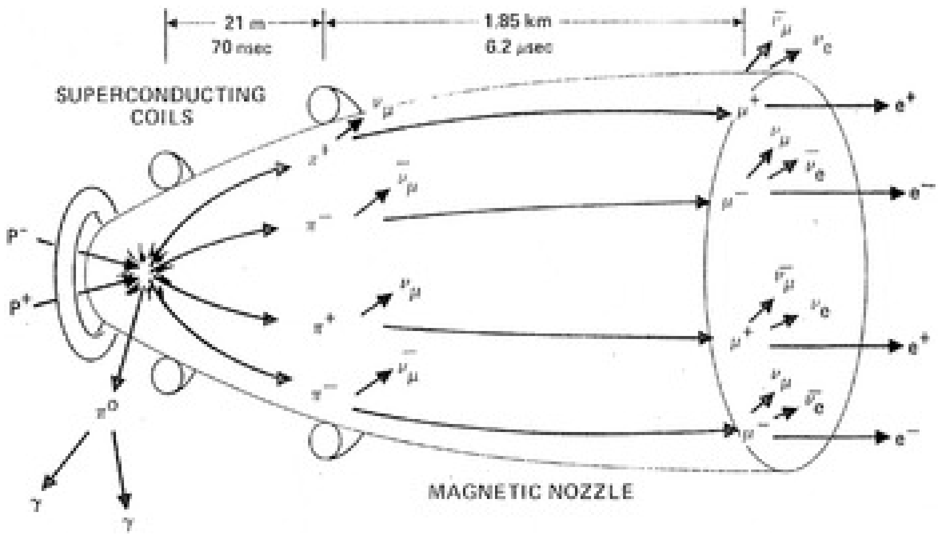


**Fig. 5 Beamed core engine to leverage the energy release of antimatter annihilation for propulsion**

$$p^{+} + p^{-} \rightarrow 1.5\pi^{+} + 1.5\pi^{-} + 2\pi^{0} \text{ (1880 MeV)} \tag{12}$$

Perhaps the most important antimatter annihilation equation is shown above, proton-antiproton annihilation. This annihilation is promptly followed by a subsequent decay into two gamma particles (as is shown in the combustion of Figure 5). This complete annihilation of matter and antimatter release roughly $9 \times 10^{16} \frac{J}{kg}$ [19]. In relation to fusion energy described in the previous section, this is nearly 1000 times more powerful. A proposed propulsion system taking advantage of this is shown in Figure 5 which leverages superconducting coils to direct the high energy particles which result from antimatter annihilation in a direction useful for thrust. The extremely high energy density of antimatter annihilation propulsion would not only allow for more efficient payload ratios, but would allow for extremely high specific impulses thus solidifying this as a very strong candidate for interstellar travel.

While antimatter seems to be 1000 times better than fusion driven propulsion systems, the engineering difficulties surrounding antimatter are monumental. For one, antimatter is hard to find and hard to create. The gigantic particle collider (CERN) in Switzerland has put in massive amounts of energy to produce antimatter particles over its operational life. Yet, if you were to take all of the antimatter particles created by CERN and annihilate them into energy it would barely power a lightbulb [20]. Nonetheless, collections of antimatter may be trapped in Earth's van Allen belts. This is compounded by the fact that current antimatteer production is likely very inefficient, meaning future processes may require less energy, may capture more antimatter, and may do so when energy is far less rare. This brings me to my final point: antimatter is extremely volatile. Humans and the stuff we use are composed of matter, precisely what antimatter is drawn to annihilate. Modern antimatter storage considerations would be technically sophisticated and would likely weigh too much given the constraints of interstellar travel. Once these engineering challenges have been surmounted, antimatter annihilation propulsion may be **the** propulsion system for use in interstellar space.

## V. Summary

While this area is promising, a myriad of engineering challenges are hindering any substantial form of interstellar exploration. With that being said, it is comforting to know that there exists physics phenomena that allow for high specific impulses and thrust to weight ratios for propulsion systems meaning that if progress continues it is likely for interstellar travel to be possible. With this discussion, it is important to realize that humanity must first become interplanetary before becoming interstellar. While these technologies may inform interstellar travel techniques, there is no reason why further research shouldn't be done to realize them since they, due to their best-of-both-worlds characteristics, may be applicable to interplanetary exploration.

As a final note, these four propulsion techniques discusses are only surface level and there are plenty of alternative opportunities for further creativity. For instance, [19] suggests a triplet propulsion schema named ACMF (antiproton-catalyzed micro-fission/fusion) taking advantage of fission, fusion and antimatter annihilation to produce an even more efficient, reliable, and attainable form of interstellar propulsion.

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