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Fundamental Constraints on Large-Scale Antimatter Rocket Propulsion

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Because antimatter could potentially be used to accelerate interstellar space probes to velocities in excess of 10% of light speed, attention is drawn to the question of whether sufficiently large quantities of antimatter could be produced in a feasible fashion. A number of different proposed methods for large-scale antimatter production are analyzed, and fundamental, broadly applicable limitations on all of these schemes are presented. The implications for antimatter rocket propulsion are discussed.

Nomenclature

A = ratio of ion mass to proton mass
B = magnetic field strength
c = speed of light
E = beam energy
E_{laser} = laser energy
e = charge of proton
e^- = electron
e^+ = positron
f = fraction of synchrotron radiation that escapes
f_A = antimatter propellant fraction
h = Planck's constant
$\hbar$ = Planck's constant $h/2\pi$
I = laser beam intensity
M_A = antimatter propellant mass
M_f = final spacecraft mass
M_i = initial spacecraft mass
M_T = total (antimatter + matter) propellant mass
m_e = mass of electron or positron
m_p = mass of proton or antiproton
n_e = electron density
n_i = ion density
n_{i1} = density of first ion type
n_{i2} = density of second ion type
P = plasma pressure
P_{ie} = ion–electron energy transfer rate
$P_{\bar{p}}$ = power converted into antiprotons
P_{syn} = synchrotron radiation power
p = proton
$\bar{p}$ = antiproton
R = radius of laser target pellet
r_i = ion gyroradius
T = time interval between laser shots
T_e = electron temperature
T_i = ion temperature
V = plasma volume
$V_{\bar{p}}$ = reaction volume producing antiprotons
V_{syn} = volume emitting synchrotron radiation
v = beam velocity
v_{exh} = rocket engine exhaust velocity
Z = ratio of ion charge to proton charge
β = ratio of plasma pressure to magnetic field pressure
γ = relativistic factor, $(1 - v^2/c^2)^{-1/2}$
ΔE = energy fluctuation of particle–antiparticle pair
Δt = lifetime of virtual particle–particle pair
ε = electric field strength
η = efficiency of antiproton production
η_{absorb} = efficiency of laser light absorption
η_{engine} = antimatter rocket engine efficiency
η_{pellet} = efficiency of laser pellet
λ_C = Compton wavelength
μ_0 = magnetic permeability
σ = antiproton production cross section
τ = confinement time of laser target pellet
τ_{col} = ion–ion Coulomb collision time
$\tau_{\bar{p}}$ = antiproton production time
ϵ_0 = electric permittivity
$\ell n\ \Lambda$ = Coulomb logarithm

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I. Introduction

PERHAPS the most challenging problem in spacecraft propulsion is the question of how a vehicle may reach nearby star systems with a travel time of less than the human lifespan. It has been proposed[1,2] that such a feat might be accomplished by using matter–antimatter annihilation reactions to propel the vehicle. In determining the feasibility of antimatter rocket propulsion the most important issue is whether sufficiently large quantities of antimatter can be created in an affordable and practical fashion. This paper will analyze and evaluate a number of different antimatter breeders that have been proposed for creating antimatter rocket propellant; this paper will also identify fundamental physical principles that limit not only those previously proposed methods but also antimatter production methods that might be considered in the future.

For rocket propulsion applications, it is desirable not only to create positrons, but also to create antiprotons, a considerably more difficult task. One reason for this desirability is that space charge limitations restrict the density of antimatter propellant that can be stored unless the antimatter is electrically neutral, thus suggesting the idea of storing the antimatter propellant in the form of antiatoms. In addition to allowing more compact storage of the antimatter propellant in a rocket, antiprotons have the further advantage that their annihilation with normal protons produces pions, which are much easier to convert to thrust in a rocket engine than the gamma rays produced by electron–positron annihilation.

This paper will analyze various methods that have been proposed for producing antiprotons. Each of the methods will be evaluated in terms of two criteria: 1) the efficiency with which energy is converted into antiprotons and 2) the production rate of antiprotons. These quantities determine the amount of power, the financial cost, and the length of time that are required to produce enough antimatter to fuel a spacecraft.

Fundamental principles governing the cost and power requirements will be presented in Sec. II. Beam–target systems, the current method of producing antiprotons, will be reviewed in Sec. III. Section IV will then evaluate a variety of proposed beam–beam antiproton production systems, including colliding proton beams,[1] colliding heavy ion beams,[3] charge-neutralized colliding proton beams,[4,5] laser–plasma interactions,[6] and colliding lepton beams.[7,8] Direct production of antiproton–proton pairs from the vacuum by means of powerful lasers, electric fields, or magnetic fields will be analyzed in Sec. V. Finally, Sec. VI will examine the implications for the large-scale use of antimatter as a means of rocket propulsion.

II. Cost and Power Requirements for Producing Antimatter

Before examining the detailed physics of antiproton production, it is worthwhile to consider the fundamental cost and power requirements that would constrain an antiproton breeder.

Consider a machine that converts input energy into the rest energy $m_p c^2$ of antiprotons at some efficiency η. Enough energy must be put into the system to create each antiproton, and so

$$\frac{\text{input energy}}{\text{mass of antiprotons}} = \frac{m_p c^2}{\eta m_p} = \frac{9.0 \times 10^{16}}{\eta} \frac{\text{J}}{\text{kg}} = \frac{2.85}{\eta} \frac{\text{GW yr}}{\text{kg}} \tag{1}$$

Because the baryon number must be conserved, the maximum theoretical value of η is 50%; a machine with this efficiency would create one proton for every antiproton. Even at this maximum efficiency, Eq. (1) indicates that it would require six dedicated full-size (1 GW of electrical output) powerplants operating for a year to provide enough energy to create 1 kg of antiprotons.

Having calculated the energy required, it is now possible to estimate the associated cost. Assuming that the cost of electricity is \$0.06/kWh (approximately the current rate), it is found that

$$\frac{\text{cost}}{\text{mass of antiprotons}} = \frac{1}{\eta} \times \frac{\$1.5 \text{ billion}}{\text{kg}} \tag{2}$$

Thus, for the maximum efficiency of $\eta = 50\%$, each kilogram of antiprotons would cost three billion dollars. While it might be possible to lower the cost estimate by getting volume discounts on the large quantities of energy consumed or by simply building one's own powerplants, it is clearly important to maximize the efficiency of the antimatter breeder if antimatter rockets are to be fueled up at an expense less than the entire federal budget.

The efficiencies of current antiproton production systems are limited by practical difficulties with the efficient collection and cooling of antiprotons.[1,2,9] However, these efficiency problems can in theory be overcome, whereas efficiency limits arising from the basic process of antiproton production are fundamental physical limitations that will apply to any foreseeable system. Therefore, in analyzing the efficiencies of candidate antiproton breeders, this paper will focus primarily on the intrinsic efficiency of the antiproton production process, not the efficiencies of the antiproton collection and cooling systems. As such, the results of this paper will represent an optimistic bound on the performance of antiproton production systems.

III. Beam–Target Systems

Current methods of producing antiprotons at Fermilab, CERN, and other particle accelerators involve pair production in inelastic collisions between a high-energy proton beam and atoms in a stationary target. For the simplest case of a hydrogen target, this reaction looks like the following:

$$p + p \rightarrow p + p + p + \bar{p} \tag{3}$$

Unfortunately, there are many possible outcomes of the inelastic collision process other than just the creation of antiprotons. The beam's energy may be converted into pions, kaons, and other particles. Typically only about 2% of the rest mass resulting from the collision is antiprotons, while only about $\eta = 2.2 \times 10^{-4}$ of the beam kinetic energy is converted into antiproton rest energy.[1] The optimum energy efficiency occurs when the proton beam incident on the stationary target has an energy of about 200 GeV (Ref. 1). Changing to a denser target material such as lead only improves the efficiency by a factor of 2 or less.[1]

Even if the proton accelerator and the antiproton collection, cooling, and storage systems were 100% efficient, the efficiency $\eta = 2.2 \times 10^{-4}$ of the beam–target collisions implies an antiproton production cost of trillions of dollars per kilogram. Therefore, beam–target systems do not appear to be particularly suitable for the large-scale production of antimatter for rocket engines, as has already been observed.[10]

For an antiproton breeder that uses inelastic collisions at relativistic speeds between two ion species of densities n_{i1} and n_{i2}, the production rate will be

$$\frac{\text{antiprotons}}{\text{s}} = \sigma c n_{i1} n_{i2} V_{\bar{p}} \tag{4}$$

(If the ions are identical in type and motion, then $\frac{1}{2}n_i^2$ should be used in place of $n_{i1}n_{i2}$.)

Approximating the antiproton production cross section for proton–proton collisions as $\sigma \approx 1$ mb $= 10^{-27}$ cm^2 near the optimum collision energy,[3] and putting the reaction volume $V_{\bar{p}}$ in cm^{-3}, one finds from Eq. (4) that

$$\frac{\text{grams of antiprotons}}{\text{year}} = 1.6 \times 10^{-33} n_{i1} n_{i2} V_{\bar{p}} \tag{5}$$

The annual production rate of a beam–target system may be estimated from Eq. (5). If the antiprotons are created when a proton beam with density $n_{\text{beam}} = 10^{10}$ cm^{-3} strikes a solid target of density $n_{\text{target}} = 4.5 \times 10^{22}$ cm^{-3}, the production rate will be

$$\frac{\text{grams of antiprotons}}{\text{year}} = 0.71 V_{\bar{p}} \tag{6}$$

It may be seen that annual production amounts in excess of 100 g are possible if the reaction volume is at least 150 cm^3, as it would be, for example, if the beam had a radius of 2 cm and the target were 12 cm long. The real limit on the production rate is the amount of power required to run the breeder, not the size of the beam–target system.

IV. Colliding Beam Systems

Whereas beam–target systems generate antiprotons in collisions between moving (beam) and stationary (target) particles, all of the particles in beam–beam antiproton production systems are moving. This difference can lead to an increase in the antiproton production efficiency, as will be discussed. Because the most frequently proposed antiproton creation methods employ beams of nucleons (protons and neutrons), most of the discussion will center on colliding nucleon beams. However, the possibility of using beams of other particle types will also be addressed.

A. General Considerations

Inelastic collisions between particles with equal but opposite momenta will obviously make more efficient use of the particle kinetic energy than would collisions between a moving beam and a stationary target. This intuition can be quantitatively clarified for relativistic particles in a straightforward manner.

Consider a beam-target system in which the beam particles have energy E and velocity v. Now compare that situation with a system in which two beams collide head-on; each beam has the same energy E' and equal but opposite velocity v'.

The beam–target and beam–beam collisions will have the same net velocity if[11]

$$v = \frac{2v'}{1 + (v'/c)^2} \tag{7}$$

Using the fact that $E = mc^2/\sqrt{1 - (v/c)^2}$, or $v/c = \sqrt{1 - (mc^2/E)^2}$, it may be seen that the stipulation of equal net velocities of collision demands that

$$E = mc^2[2(E'/mc^2)^2 - 1] \tag{8}$$

This relationship between E and E' can be simplified for $E' > 2mc^2$:

$$E \approx 2E'^2/mc^2 \tag{9}$$

Since protons have a rest energy $mc^2 = 0.938$ GeV ≈ 1 GeV, two colliding 10-GeV proton beams (or a total energy of 20 GeV) will be comparable to a 200-GeV proton beam hitting a stationary target. Therefore, colliding 10-GeV proton beams have an antiproton production efficiency that is approximately 200 GeV/20 GeV = 10 times larger than the efficiency of a beam–target system. Thus for colliding-beam antiproton breeders, $\eta \approx 2.3 \times 10^{-3}$. This antiproton production efficiency is actually a fundamental upper bound on all colliding nucleon beam systems. However, the antiproton production rate can vary widely between different types of systems, as will be shown.

B. Proton Colliders

It is desirable to keep the colliding beam densities as high as possible so that the antiproton production rate will be as large as possible, as shown by Eq. (4). However, the density of a nonneutral particle beam is limited by space charge effects. Electrostatic repulsion among beam particles of like charge must be balanced by the application of a confining B. This requirement constrains the beam density to be less than the relativistic Brillouin limit[12–14]:

$$n \leq \frac{B^2/2\mu_0}{\gamma mc^2} \tag{10}$$

where n is the density of the charged particles in m^{-3}, B is the magnetic field strength in tesla, $\mu_0 = 4\pi \times 10^{-7}$ H/m is the magnetic permeability of free space, $\gamma \equiv 1/\sqrt{1 - (v/c)^2}$ is a function of the particle velocity, and m is the mass of the particles. The right-hand side of Eq. (10) may be interpreted as the ratio of the magnetic field's energy density to the relativistic particle energy.

Keeping B in tesla, putting n in cm^{-3}, and expressing the relativistic particle energy γmc^2 in GeV, the Brillouin limit may be rewritten as

$$n \leq 2.48 \times 10^9 (B^2/\gamma mc^2) \tag{11}$$

Even for a very high magnetic field strength of $B = 50$ T and a particle energy of $\gamma mc^2 = 10$ GeV, the Brillouin-limited density is only

$$n \leq 6.2 \times 10^{11} \text{ cm}^{-3} \tag{12}$$

The antiproton production rate of a breeder that uses two colliding proton beams, each with space-charge-limited density $n_i \sim 6 \times 10^{11}$ cm^{-3}, is found from Eq. (5) to be

$$\frac{\text{grams of antiprotons}}{\text{year}} \approx 5.8 \times 10^{-10} V_{\bar{p}} \tag{13}$$

Even if the beams have a cross-sectional area of ~10 cm^2 and overlap for a distance of ~10 m, the production rate will only be ~6×10^{-6} g/year. This rate is much lower than that of a large beam-target system and is much too low to be of interest for producing antimatter rocket propellant.

C. Uranium Ion Colliders

To overcome the space charge limitations on proton–proton colliders, it has been proposed to collide singly ionized ^{238}U ions instead of protons.[3] The inspiration for this idea is that the power carried by a space-charge-limited ion beam increases like $(A/Z)^2$, where the atomic mass number A is the ratio of the ion mass to the proton mass m_p and Z is the ratio of the ion charge to the proton charge (e).

Unfortunately, this idea does not seem to have as much merit as it might first appear. Because the Brillouin limit density is inversely proportional to the particle mass, the beam density of ions with mass $m = Am_p$ will be A times lower than the corresponding proton beam density. On the other hand, the average nucleon density will be A times the ion density, or the same as the nucleon density of the proton beam.

At 10 GeV per nucleon, the λ_C of the nucleons is

$$\lambda_C \equiv h/\gamma m_p c = 1.1 \times 10^{-16} \text{ m} = 0.11 \text{ fm} \tag{14}$$

in which $h = 6.626 \times 10^{-34}$ J·s is Planck's constant. Since the wavelength is roughly an order of magnitude smaller than the size of a nucleon, during the collision process the nucleons will see other individual nucleons, not the nucleus as a whole. The cross section for antiproton production from these nucleon–nucleon interactions will be roughly the same as it was for proton–proton interactions, and so for a given reaction volume the production rate will be approximately the same as it was for colliding proton beams. As previously discussed, this production rate is too low to be of interest for fueling large-scale antimatter rockets.

The phenomenon that prompted this concept, namely the scaling of the circulating beam power as $(A/Z)^2$, still must be explained. This scaling is simply because the minimum beam radius that can be maintained by the magnetic field is $r_i \equiv \gamma mc/ZeB$, which increases like (A/Z); the power is proportional to the square of the beam radius (the beam's cross-sectional area) and thus $(A/Z)^2$. The circulating power of a proton beam could be increased just as much by keeping the beam density constant but widening the beam.

Even if the production rate were higher for colliding uranium atoms than for colliding protons, there would be unpleasant difficulties to face. It would be necessary to sift through massive quantities of fission fragments and other nuclear shrapnel just to find the antiprotons. Moreover, the moment that the antiprotons were created, a large number of them might be immediately annihilated within the transitory compound nucleus formed during the collision process.

One is therefore forced to dismiss the proposal to breed antiprotons in a colliding uranium beam machine. There are several difficulties uniquely inherent in the idea, while its performance would at best be comparable to that of a proton–proton collider (which is limited to antiproton production rates too low to be interesting).

D. Neutralized Particle Beams

One obvious tactic for overcoming the space-charge limitation on the antiproton production rate of colliding nucleon beams is to add electrons to the system to neutralize the beams.

Relativistic colliding beam systems that employ this method have been proposed.[4,5]

In principle, the ion velocity distribution may be either thermal or relatively monoenergetic. However, if the ions are thermal, they will exert a relatively large pressure on the confining magnetic field. Magnetohydrodynamic equilibrium for the system requires that[15]

$$\beta \equiv \frac{P}{B^2/2\mu_0} \leq 1 \tag{15}$$

in which P is the maximum pressure in the ion-electron plasma and B is the maximum strength of the external magnetic field confining the plasma.

For a plasma containing relativistic ions, $P \sim n_i T_i \sim n_i \gamma m_i c^2$, where the ions have n_i, T_i, m_i, and relativistic factor $\gamma \equiv 1/\sqrt{1 - (v/c)^2}$. Using this information, the maximum ion density allowed by Eq. (15) is

$$(n_i)_{\max} \sim \frac{B^2/2\mu_0}{\gamma m_i c^2} \tag{16}$$

Therefore, the $\beta < 1$ constraint on neutralized thermal ion distributions yields essentially the same maximum density as the Brillouin limit on unneutralized particle beams. Such densities are too low to be of interest. (It should be remarked that this is only true for relativistic plasmas, such as those considered here for antiproton production. In nonrelativistic plasmas, such as those contemplated for controlled fusion, the β-limited density of neutral plasmas is much higher than the Brillouin-limited density of nonneutral plasmas, so that it is highly advantageous to neutralize such plasma systems.)

Relatively monoenergetic ion velocity distributions may also be contemplated. Specifically, consider two neutralized ion beams that collide head-on. Ion–ion collisions will produce antiprotons on a timescale of $\tau_{\bar{p}} = 1/(n_{i1}\sigma c)$, where n_{i1} is the ion density of one of the beams, σ is the antiproton production cross section, and the beams are moving nearly at c. Ion–ion collisions will thermalize the ion distribution on a timescale of τ_{col}. The relativistic expression for the collision time may be estimated by using the usual nonrelativistic τ_{col} (Ref. 16) with the changes $T_i \to E_i/3$ and $m_i \to \gamma m_i$:

$$\tau_{\text{col}} = \frac{4\pi^{3/2}\epsilon_0^2\sqrt{\gamma m_i}E_i^{3/2}}{\sqrt{3}n_{i1}(Ze)^4\,\ell n\,\Lambda} \tag{17}$$

Taking the ratio of τ_{col} and $\tau_{\bar{p}}$, one finds

$$\frac{\tau_{\text{col}}}{\tau_{\bar{p}}} = \frac{4\pi^{3/2}\epsilon_0^2\sigma c\sqrt{\gamma m_i}E_i^{3/2}}{\sqrt{3}(Ze)^4\,\ell n\,\Lambda} \tag{18}$$

For $\sigma = 1$ mb $= 10^{-31}$ m^2 (Ref. 3), $\gamma = 11$, $E_i = 10$ GeV $= 1.60 \times 10^{-9}$ J, $Z = 1$, and $\ell n\,\Lambda = 20$, this ratio is

$$\tau_{\text{col}}/\tau_{\bar{p}} = 2.0 \times 10^4 \tag{19}$$

Therefore, the ion–ion collisional thermalization time is much longer than the antiproton production time, and so it should be possible to keep the ion beams relatively monoenergetic. Of course, this simple calculation has neglected ion thermalization caused by the inelastic ion collisions that produce antiprotons, pions, kaons, etc. Such effects would have to be included in a more detailed examination of the concept.

Neutralized plasma antiproton breeders would also face important efficiency limitations. Because these systems still rely on nucleon–nucleon collisions to produce antiprotons, the previously calculated upper bound on the efficiency still applies, $\eta \approx 2.3 \times 10^{-3}$. However, for actual antiproton breeders, the efficiency could be far smaller than this value. In addition to the problems with efficient antiproton collection and cooling that are faced by all antiproton production approaches, neutralized-beam systems face other problems.

One of the most important problems is the power loss because of synchrotron radiation. This radiation loss must be compared with the energy converted into antiprotons to gauge its severity. For electron temperatures comparable to or less than the electron rest energy, the power radiated as synchrotron energy may be approximated by[17]

$$P_{\text{syn}} \approx 6.21 \times 10^{-20} B^2 n_e T_e[1 + \tfrac{5}{2}(T_e/m_e c^2)] f V_{\text{syn}}\ \text{W} \tag{20}$$

in which B is the confining magnetic field strength in tesla (instead of gauss as in Ref. 17), n_e is the electron density in cm^{-3}, T_e is the electron temperature in eV, f is the net fraction of the synchrotron radiation that cannot be reflected back into the plasma and reabsorbed there, and V_{syn} is the effective volume from which synchrotron radiation is emitted.

Since the radiation losses will depend on the electron temperature, it is necessary to calculate the equilibrium electron temperature based on energy exchange with the relativistic ions. Recognizing that for relativistic particles of species j, $m_j \to \gamma_j m_j$ and $T_j = E_j/3 = \gamma_j m_j c^2/3$, and assuming $Z = 1$, the expression for the relativistic P_{ie} is[18]

$$P_{\text{ie}} = \frac{e^4 c n_i n_e\,\ell n\,\Lambda}{12\pi\epsilon_0^2 T_e} V \tag{21}$$

in which it has been assumed that $T_i >> T_e$ and that the heat transfer occurs throughout V.

Setting the rate of electron cooling by synchrotron radiation equal to the rate of electron heating by Coulomb friction with the energetic ions, $P_{\text{syn}} = P_{\text{ie}}$, one discovers

$$\left(\frac{T_e}{m_e c^2}\right)^2 \left[1 + \frac{5}{2}\left(\frac{T_e}{m_e c^2}\right)\right] = \ell n\,\Lambda \cdot \frac{1}{f} \cdot \frac{V}{V_{\text{syn}}} \cdot \frac{m_e}{m_p} \cdot \frac{n_i m_p c^2 \mu_0}{4B^2} = \ell n\,\Lambda \cdot \frac{1}{f} \cdot \frac{V}{V_{\text{syn}}} \cdot \frac{m_e}{m_p} \cdot \frac{1}{8\gamma_i} \frac{n_i}{(n_i)_{\text{Brillouin}}} \tag{22}$$

where the ion density has been expressed relative to the Brillouin-limited ion density $(n_i)_{\text{Brillouin}}$.

For $\ell n\,\Lambda \sim 20$, $f \sim 0.1$ (most of the radiation is reflected back into the plasma), $V/V_{\text{syn}} \sim 10$ (the magnetic field is excluded from most of the plasma's volume), $\gamma_i \sim 11$, and $n_i/(n_i)_{\text{Brillouin}} \sim 100$, the temperature is found to be

$$T_e \sim 0.68 m_e c^2 \approx 350\ \text{keV} \tag{23}$$

While the exact value of the electron temperature is dependent on the assumed values of the key parameters, it is clear that for a relatively wide range of reasonable values for these parameters the electron temperature will be on the order of the electron rest energy.

Dividing the synchrotron loss power by the power $P_{\bar{p}} = \sigma c n_i^2 m_0 c^2 V_{\bar{p}}/2$, which is converted into the rest energy of antiprotons (where $V_{\bar{p}}$ is the effective volume in which the antiproton-producing reactions occur), one finds

$$\frac{P_{\text{syn}}}{P_{\bar{p}}} = \frac{64\pi}{3}\gamma_i f \frac{(n_i)_{\text{Brillouin}}}{n_i} \frac{V_{\text{syn}}}{V_{\bar{p}}} \frac{r_0^2}{\sigma} \left(\frac{T_e}{m_e c^2}\right) \left[1 + \frac{5}{2}\left(\frac{T_e}{m_e c^2}\right)\right] \tag{24}$$

in which $r_0 \equiv e^2/4\pi\epsilon_0 m_e c^2 = 2.818 \times 10^{-13}$ cm is the classical electron radius.

Estimating that $\gamma_i \approx 11$, $f \sim 0.1$, $n_i/(n_i)_{\text{Brillouin}} \sim 100$, $V_{\text{syn}}/V_{\bar{p}} \sim 1$, $\sigma \approx 10^{-27}$ cm^2, and $T_e \sim 0.68 m_e c^2$, the power ratio becomes

$$P_{\text{syn}}/P_{\bar{p}} \sim 110 \quad (25)$$

According to this rough estimate, about 110 times more input energy will be lost in the form of radiation than will be converted into antiprotons. [It must be remembered that because of competing reactions, about 430 (=1/η) times more input energy will be converted into pions, kaons, and residual kinetic energy than will be converted into the rest energy of antiprotons.] Bremsstrahlung radiation will also be emitted by the electrons, but under these conditions it should be less severe than the synchrotron radiation.[17] Of course, the precise radiation losses depend on the particular system parameters that are chosen. If the confining magnetic field penetrates into a larger volume of the plasma or if more of the radiation escapes than has been assumed, the radiation losses could be substantially larger than the value that has been calculated here.

Particle losses must also be taken into account in analyzing particular actual systems. Since these losses are more design-specific than the radiation losses, they have not been considered here. However, particle losses may prove at least as great of a problem as radiation losses, as witnessed by the history of the controlled fusion program.

The electrons will exert a pressure that must be included in the β limit in Eq. (15). Assuming the electron pressure to be $P = n_e T_e \sim n_e m_e c^2$, neglecting any ion pressure, setting $Z = 1$, choosing $B = 50$ T, and using the charge neutrality condition $n_i = n_e$, the maximum ion density allowed by Eq. (15) is

$$(n_i)_{\max} \sim \frac{B^2/2\mu_0}{m_e c^2} \approx 1 \times 10^{16}\ \text{cm}^{-3} \quad (26)$$

For $n_{i1} = n_{i2} \approx 5 \times 10^{15}$ cm^{-3}, Eq. (5) becomes

$$\frac{\text{grams of antiprotons}}{\text{year}} \approx 0.04 V_{\bar{p}} \quad (27)$$

in which $V_{\bar{p}}$ is in cm^3. Therefore, antiproton production rates well in excess of 1 g/year might be achieved with reasonable reaction volumes.

In summary, antiproton production rates of neutralized beam–beam systems may approach those of beam–target systems. However, the improved energy efficiency inherent in beam–beam vs beam–target collisions would be largely offset by energy losses because of radiation from the electrons and particle losses from the confinement system.

E. Laser–Plasma Interactions

To overcome the limitations of magnetically confined neutral plasmas, one could consider changing to inertially confined neutral–plasma antiproton breeders that would be analogous to inertial confinement fusion (ICF). One such system that has been proposed involves coupling between a laser beam and the individual ions in a plasma.[6] Energy from the beam is converted into kinetic energy of the oscillating ions. After the ions have been accelerated to energies of a few GeV, they can produce antiprotons via ion–ion collisions.

While the production of antiprotons via inelastic ion collisions would have the same intrinsic efficiency limitations as it did when the ions were simply accelerated by a particle accelerator, the potential advantage of using a laser is that the plasma might start out as an inertial-confinement-fusion-type pellet; as such, the plasma would have a density comparable to solids ($\sim 10^{22}$–10^{23} cm^{-3}) instead of the relatively low plasma density found inside a particle accelerator. Because the reaction rate is proportional to the square of the density, the antiproton production rate would be much larger. Thus the arguments in favor of laser–plasma antiproton breeders are ones of production rate, not production efficiency.

In fact, the actual efficiency of a laser-based breeder would be even lower than that of a beam–target system. The efficiency is the product of the already low efficiency inherent in inelastic–collision-induced antiproton production, the laser efficiency (presumably much lower than the ~50% efficiency of a linear particle accelerator), and the efficiency with which the laser light can be absorbed and fairly homogeneously converted into the kinetic energy of most of the ions in the pellet. This latter absorption efficiency will likely be quite low; the laser beam, unable to penetrate the dense central plasma because of the high cutoff plasma frequency there, can only deliver its energy to the low-density halo of plasma surrounding the central pellet. Methods for converting the ion energies of the outer pellet into ion energies in the inner region of the pellet are not noted for their high efficiencies; inertial confinement fusion implosion techniques for such a conversion have about a 5% efficiency.[15]

Having noted the potential problems with the production efficiency, the production rate argument should now be evaluated numerically. Let R be the pellet radius; a typical size suggested in Ref. 6 is 30 μm. If the ions in the pellet acquire relativistic energies, they will be moving at almost light speed, so that the confinement time $\tau \equiv R/c$ would be 10^{-13} s for a 30-μm pellet. Let T be the interval between pellet shots; this time will optimistically be assumed to be only 0.1 s. Thus, while the production rate during the laser–plasma interaction is greatly enhanced because of the high densities, it is apparent that this advantage is largely lost because the system is only productive for a fraction $\tau/T \sim 10^{-12}$ of the time.

Continuing with the evaluation of the antiproton production rate, $n_i = 4.5 \times 10^{22}$ cm^{-3} is the density of a solid hydrogen pellet, and η_{pellet} will represent the fraction of the pellet that is efficiently utilized to create a relativistic, colliding, antiproton-breeding hydrogen plasma. Then the production rate of antiprotons from Eq. (5) will be

$$\frac{\text{grams of antiprotons}}{\text{year}} = 1.6 \times 10^{-33} \left(\frac{1}{2} n_i^2\right) \left(\frac{4}{3}\pi R^3\right) \left(\frac{\tau}{T}\right) \eta_{\text{pellet}} = 1.8 \times 10^{-7} \eta_{\text{pellet}} \quad (28)$$

Even if $\eta_{\text{pellet}} = 100\%$, this production rate does not compare favorably with that obtainable from a good system with a proton beam hitting a solid target. Because of the enormous difficulties of getting the laser light to be evenly and efficiently absorbed throughout most of the pellet, η_{pellet} will probably be quite low, and the production rate will be abysmal.

One could also cast doubt on this breeder concept by evaluating the size of the laser that would be required. Assuming that the laser must provide enough energy to bring all of the protons and electrons in the pellet up to 10 GeV of energy, and designating η_{absorb} to be the efficiency with which the laser light accomplishes this goal, one finds the necessary laser energy to be

$$E_{\text{laser}} = (n_i + n_e)\left(\tfrac{4}{3}\pi R^3\right)(10^{10}\ \text{eV})[1.6 \times 10^{-19} (\text{J/eV})](1/\eta_{\text{absorb}}) \quad (29)$$

Using the same parameters as before, it is found that

$$E_{\text{laser}} = 16\ \text{MJ}/\eta_{\text{absorb}} \quad (30)$$

Not only must the laser deliver 16 MJ, a higher energy than even that required of proposed ICF drivers, but it must also deliver that energy within the 0.1-ps period before the pellet blows apart. ICF drivers at least have the luxury of yielding up their energy over a period of a nanosecond or longer.[19] (In practice, the laser energy would probably have to be far greater than 16 MJ because of the many problems with efficient absorption of the energy by the pellet's protons.)

It should also be noted that it is not possible to find a pellet size that leads to more optimistic results. If one scales up to larger pellet sizes in an attempt to increase the annual production rate, the required laser energy becomes even more unreachable.

To sum up the outlook for the sort of inertial confinement breeders outlined by Ref. 6, their efficiency and maximum production rate are much lower than those of the beam–target and neutralized beam–beam systems discussed earlier. Furthermore, such inertial confinement breeders would require laser pulses of unrealistically high energies and short pulse widths, and many great difficulties would have to be overcome to efficiently convert the laser energy into kinetic energy of the majority of the ions within the pellet. Inertial confinement breeders using particle beam drivers instead of laser drivers would encounter similar problems. Incidentally, it should also be noted that there are several errors in Ref. 6, which improperly calculates the antiproton production efficiency and production rate and graphs the trajectories of plasma particles that are apparently moving faster than light.

F. Colliding Beams of Other Particles

It is not readily apparent that there are other types of colliding-beam antiproton breeders that are better than colliding nucleon beam systems. Generally, the antiproton production rates and/or efficiencies seem to be worse for other systems than for nucleon–nucleon collisions.

For example, a process that has been extensively studied in particle accelerators is electron–positron collisions.[7,8,20] The cross section for producing antiprotons peaks near the J/Ψ resonance at a total c.m. energy of approximately 3.1 GeV for the electron and positron beams.[7,8] Using Eq. (11) with a magnetic field strength of 50 T and an energy per beam of 1.55 GeV, the Brillouin-limited density of the electron (e^-) beam and the positron (e^+) beam is found to be

$$n_{e^-} = n_{e^+} \leq 4 \times 10^{12}\ \mathrm{cm}^{-3} \tag{31}$$

Under these conditions, the cross section for producing antiprotons is approximately 9×10^{-8} (Ref. 7). For $n_{e^-} = n_{e^+} \approx 4 \times 10^{12}\ \mathrm{cm}^{-3}$ and $V = 10^4\ \mathrm{cm}^3$, the antiproton production rate is

$$\frac{\text{grams of antiprotons}}{\text{year}} << 2 \times 10^{-8}\ \text{g/year} \tag{32}$$

This production rate is much lower than even that of the proton–electron plasma considered in Sec. IV.D.

V. Pair Production from the Vacuum

From quantum field theory it is known that pairs of virtual particles and antiparticles continually appear out of the vacuum and then disappear back into the vacuum unless they are given enough energy to become real. This fact suggests that another method of producing antiprotons would be to use intense electric, magnetic, or electromagnetic fields to impart energy to virtual antiprotons that appear in this fashion and thereby convert them into real antiprotons. (This might be regarded as the "Velveteen Rabbit" method of producing antimatter.) The threshold field strengths needed for this purpose may be estimated from simple physical arguments.

A. Pair Production from Electric Fields

The lifetime of a virtual particle–antiparticle pair may be estimated from the uncertainty principle between energy and time, $\Delta E \Delta t \approx \hbar$, where $\hbar \equiv h/2\pi$. Since the minimum energy fluctuation ΔE required to produce the particles is equal to their rest energy, the lifetime of the pair may be approximated by

$$\Delta t \approx \hbar/2mc^2 \tag{33}$$

To prevent these virtual particles from rapidly disappearing back into the vacuum, a very strong electric field ε can be applied; if the particles travel far enough along the electric field during Δt, they can acquire an energy greater than their rest mass energy and become real. Approximating the particle speed as close to light speed, this condition on making the pair real can be expressed as

$$mc^2 = e\varepsilon\Delta x \approx e\varepsilon c\Delta t \approx e\varepsilon c(\hbar/2mc^2) \tag{34}$$

From this constraint it may be seen that the electric field must exceed a certain critical value to impart enough energy to the particle–antiparticle pairs:

$$\varepsilon \geq \frac{2(mc^2)^2}{\hbar ec} \tag{35}$$

If the particle mass is expressed as a dimensionless multiple of the electron mass $\mu \equiv m/m_e$, and the constants are evaluated, the constraint on the electric field becomes

$$\varepsilon \geq 2.7 \times 10^{18}\mu^2\ \mathrm{V/m} \tag{36}$$

Perhaps the easiest way to generate extremely intense electric fields would be to focus a very powerful laser beam down to its diffraction limit. The value of the critical electric field given in Eq. (36) is equivalent to a laser beam intensity $I = \varepsilon^2/2\sqrt{\mu_0/\epsilon_0}$, where $\sqrt{\mu_0/\epsilon_0} = 377\ \Omega$, or

$$I \geq 9.3 \times 10^{29}\mu^4\ \mathrm{W/cm^2} \tag{37}$$

For proton–antiproton pairs, $\mu = 1836$, yielding the result

$$I \geq 1.1 \times 10^{43}\ \mathrm{W/cm^2} \tag{38}$$

For reference, even if the 3×10^{13} W peak power of the Nova laser at the Lawrence Livermore National Laboratory were focused down to its diffraction limit of a 0.35-μm-diam spot,[19] the intensity would be only $3 \times 10^{22}\ \mathrm{W/cm^2}$. Clearly, the required intensity is far too large for the direct conversion of laser energy into antiproton–proton pairs to be of any practical interest in the foreseeable future.

Incidentally, it has been optimistically assumed that only protons and antiprotons are pair-produced. In all probability most of the energy would go into pair production of numerous electron–positron pairs plus some pions and kaons, although perhaps some energy resonance effect could be discovered that would allow only proton–antiproton pairs to be produced if the system were set up properly.

B. Pair Production Resulting from Magnetic Fields

Just as intense electric fields can impart energy to virtual particles, intense magnetic fields could also theoretically be used to convert virtual particles into real ones. For example, setting the lowest Landau energy level[21] of a virtual particle in a magnetic field equal to the rest energy needed to make that particle real, one finds

$$mc^2 = \hbar eB/2m \tag{39}$$

For particle–antiparticle production, the magnetic field must be at least

$$\begin{aligned} B &\geq 2(mc)^2/\hbar e \\ &\geq 8.84 \times 10^9\mu^2\ \mathrm{T} \end{aligned} \tag{40}$$

For antiprotons, the minimum magnetic field is

$$B \geq 3.0 \times 10^{16}\ \mathrm{T} \tag{41}$$

The magnetic field strength required for antiproton production is far beyond the reach of foreseeable technology.

Using the relation $|\varepsilon| = c|B|$ from elementary electromagnetic wave theory, it may be seen that the magnetic field threshold in Eq. (40) is fully comparable to the electric field threshold in Eq. (35). This result is not surprising considering that electric and magnetic fields are part of the same fundamental force.

VI. Antimatter Rocket Engines

In view of the extreme difficulty and cost of producing substantial quantities of antimatter, antimatter propulsion should probably be reserved for cases in which there are no other propulsion options. While such options exist for propelling nonrelativistic spacecraft and even for accelerating interstellar probes to significant fractions of light speed (via fusion or beamed power), there are few other good options for decelerating interstellar probes as they near their targets. Antimatter propulsion could conceivably serve as the basis for a compact, onboard, low-mass deceleration system for interstellar probes. (The primary alternative would be to use a magnetic sail[22] or other drag-based method of deceleration, but that would require decades of deceleration time and the deployment of exceedingly large and potentially vulnerable structures.)

One possible antiproton engine is described in Refs. 23 and 24. In this design, a beam of antiprotons collides with a beam of heavy nuclei such as uranium ions. Each antiproton annihilates with either a proton or a neutron at the surface of one of the heavy nuclei and produces pions. On average, 25–50% of the pions will enter the nucleus and deposit their energy there. If the nucleus then fissions, this energy will be converted into the kinetic energy of the fission fragments, which can be directed out of a magnetic nozzle with an exhaust velocity in the range $v_{\mathrm{exh}} \approx 0.07\text{–}0.09c$.

To produce much higher exhaust velocities, another engine design has been proposed.[23] In this scheme, the antiproton beam annihilates with a beam of protons, thereby producing charged pions (~60% of the reaction products) and neutral pions (~40%). The charged pions can be directed out of a magnetic nozzle at velocity $v \approx 0.95c$. Unfortunately, the neutral pions immediately decay into gamma rays and are lost, so the effective exhaust velocity is only $v_{\mathrm{exh}} \approx 0.95c \times 60\% \approx 0.5\text{–}0.6c$. (Note that the effective exhaust velocity for this type of engine is often erroneously given as $0.95c$ without taking into account the loss of the neutral pions.)

Yet another approach that has been suggested uses antiprotons to catalyze the reactions in a fission or fusion pulse propulsion system.[25–27] The maximum exhaust velocities of such systems would generally be limited by the velocities of the fission or fusion nuclear reaction products to, at most, a few percent of light speed.

If desired, antimatter could also power engines with much smaller exhaust velocities. For example, antiproton–proton annihilation reactions could be used to heat hydrogen propellant and attain specific impulses on the order of 1000 s.[28–31]

It is beneficial at this point to consider the performance of a generalized antimatter rocket engine.[32,33] Such an engine would combine a certain amount of antimatter (total mass M_A) with an equal or larger amount of matter. If M_T is the total mass of the propellant (matter and antimatter together), then it is useful to think in terms of the antimatter fraction $f_A \equiv M_A/M_T$. To avoid wasting antimatter, f_A should be no more than one-half. Let v_{exh} be the average exhaust velocity of particles propelled out of the rocket by the matter–antimatter annihilation energy, and let η_{engine} be the engine efficiency or the fraction of the annihilation energy that is absorbed in the expelled propellant. It is possible to express the antimatter fraction f_A as a function of the exhaust velocity. The annihilation energy is converted with efficiency η_{engine} into the kinetic energy of the rest of the propellant, so that

$$2M_A c^2 \eta_{\mathrm{engine}} = (M_T - 2M_A)c^2 \left[\frac{1}{\sqrt{1 - (v_{\mathrm{exh}}/c)^2}} - 1\right] \tag{42}$$

After some algebra, the antimatter fraction is found to be

$$f_A \equiv \frac{M_A}{M_T} = \frac{1}{2} \times \frac{1 - \sqrt{1 - (v_{\mathrm{exh}}/c)^2}}{1 + (\eta_{\mathrm{engine}} - 1)\sqrt{1 - (v_{\mathrm{exh}}/c)^2}} \tag{43}$$

For $v_{\mathrm{exh}} < c/2$ and $\eta_{\mathrm{engine}} >> (v_{\mathrm{exh}}/c)^2/2$, f_A may be well approximated by

$$f_A \approx \frac{1}{4\eta_{\mathrm{engine}}} \left(\frac{v_{\mathrm{exh}}}{c}\right)^2 \tag{44}$$

For a desired exhaust velocity of $v_{\mathrm{exh}} = 0.1c$ and $\eta = 25\%$, the antimatter fraction is

$$f_A \approx 1/100 \tag{45}$$

Thus, for every 100 kg of total propellant mass, only 1 kg of antimatter is needed. This fact helps to lower the potential cost of antimatter rockets greatly, but unfortunately the cost is still too high, as may be illustrated by the following calculation.

Consider a spacecraft that changes its velocity by $\Delta v = 0.1c$ and has an exhaust velocity $v_{\mathrm{exh}} = 0.1c$. From the ideal rocket equation, M_i and M_f are related by

$$\frac{M_i}{M_f} = e^{\Delta v/v_{\mathrm{exh}}} = e \tag{46}$$

Therefore, the total propellant mass must be $(e - 1)M_f$, and the antimatter mass must be 1/100 of that amount

$$M_A = [(e - 1)/100]M_f \tag{47}$$

Equation (47) shows that for each metric ton (1000 kg) of dry spacecraft mass, 17.18 kg of antimatter is needed.

As has been demonstrated, the most efficient foreseeable antiproton breeder would employ colliding nucleon beams and would have a maximum efficiency $\eta \approx 2.3 \times 10^{-3}$. Optimistically ignoring the generally low antiproton production rate of colliding nucleon beams and using this efficiency value, Eq. (1) shows that 21,000 GW-years of input energy would be required to produce the required 17.18 kg of antiprotons. (For reference, a typical full-size modern nuclear powerplant produces ~1 GW of electrical power.) From Eq. (2), this much energy would cost 11 trillion dollars at current electric rates. The requirements of 11 trillion dollars and 21,000 GW-years per 1000 kg of dry spacecraft mass are clearly too large by several orders of magnitude.

Two other problems intrinsic to antimatter rocket propulsion should also be mentioned briefly. First of all, it is relatively difficult to induce the high-energy pions produced by proton–antiproton annihilation to deposit their energy within a propellant mass to lower the exhaust velocity and raise the thrust level. Pions can travel several tens of centimeters, even through liquids or solids before they have deposited most of their energy.[1] This problem prompts approaches such as antiproton annihilation within large nuclei.[23,24] The second problem is that the gamma rays produced by neutral pion decay and by electron–positron annihilation may pose a serious radiation hazard to delicate parts of the engine and will necessitate the use of a considerable amount of shielding to protect the rest of the vehicle.[34]

VII. Conclusions and Future Directions

A number of different schemes for producing large quantities of antiproton rocket propellant have been examined, and the efficiency and production rate of each scheme have been scrutinized.

Currently, nucleon beam–target systems are used to create antiprotons. While the production rates that could be obtained from large systems of this type are not bad, the maximum efficiency is far too low to be useful for the large-scale production of antimatter rocket propellant.

Colliding-nucleon-beam antiproton breeders would have a maximum efficiency nearly an order of magnitude higher than beam–target systems, but foreseeable colliding-beam breeders have been shown to have low antiproton production rates as well as other potential problems. Unneutralized colliding beams of nucleons are limited to uninteresting production rates by the Brillouin limit, and neutralized thermal nucleon beams are similarly constrained by the $\beta < 1$ requirement. Neutralized, nearly monoenergetic colliding nucleon beams may be able to attain higher antiproton production rates, but they would be hampered by energy losses such as radiation from the electrons and particle losses from the confinement system. Two specific proposed colliding-nucleon systems, uranium ion colliders and laser–plasma interactions, have been shown to suffer from additional fatal flaws. Beams consisting of particles other than nucleons appear to have even lower antiproton production rates than nucleon beam techniques, but it is possible that a useful particle beam type has been overlooked.

For all antiproton production methods involving pair production from the vacuum in intense electromagnetic fields, the threshold field strength was found to be far too large to consider. As a further complication, there appears to be no readily foreseeable method of selectively producing only proton–antiproton pairs, even if such field strengths could be attained.

Clearly, much work remains to be done to produce an antimatter breeder capable of actually fueling an interstellar space probe. Both the energy efficiency and the annual production rate need to be increased, preferably by several orders of magnitude.

Although there are various possible ways to improve the efficiency of handling the antiprotons once they are created, the fundamental limitation on producing antiprotons remains the competing reactions that convert most of the input energy into pions and other products instead of antiprotons. It would be very desirable to find a method for circumventing this problem. One possibility is that there might be favorable resonance effects at certain system parameters that would allow the creation of many more antiprotons than pions and other particles.[1] Another possible solution would be to reabsorb the pions within the breeder material or otherwise convert the pions back into useful energy to reduce the net loss. For instance, it is conceivable that some of the pions could be converted to antiprotons by a variety of potential reactions.[7,8] The efficiency might also be increased by directly converting the kinetic energy of all of the reaction products back into electricity using techniques such as those in Refs. 35 and 36, or by reusing the high-energy reaction products in further antiproton-producing collisions. These various techniques might potentially be applied to beam-target breeders to greatly improve the efficiency while maintaining a large antiproton production rate. Any other categories of antiproton production methods that have not been discussed in this paper should also be examined in the future.

Of course, in addition to further research on methods of producing antimatter, a great deal more work should be done both on techniques for its handling and storage and on engine designs which can best exploit antimatter as a propellant. To minimize the amount of antimatter required for a mission, the antimatter storage and propulsion systems should have as little mass as possible. To produce enough antimatter for interstellar rockets, it will also be necessary to devise very large power-generation systems that can produce energy much more cheaply than current methods. For example, large solar-power arrays in orbit near the sun might be considered.[1]

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