Antiproton Annihilation Propulsion

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Antimatter represents a highly concentrated form of energy storage, since the antimatter converts all of its mass to energy upon annihilation with normal matter. The antimatter should be in the form of antiprotons since, unlike antielectrons, the antiproton does not convert into gamma rays upon annihilation, but instead two-thirds of the energy is emitted as charged particles (pions) whose kinetic energy can be converted into thrust by interaction with a magnetic field nozzle or a working fluid. Antiprotons are already being generated, captured, cooled, and stored at a number of particle physics laboratories around the world, albeit in small quantities. A number of techniques for the efficient generation, long-term storage, and effective utilization of milligram quantities of antiprotons for space propulsion are discussed.

Introduction

IN this paper, a new high specific impulse, high-thrust propulsion system, based on the generation, storage, and utilization of antiprotons is discussed. It has long been realized that antimatter would be a valuable propulsion energy source because it allows for the complete conversion of mass to energy. Early studies of the concept by Sänger[1] assumed that the antimatter would be antielectrons (positions), which interact with electrons to produce 0.511 MeV gamma rays. Sänger tried unsuccessfully to invent electron-gas mirrors to direct these short wavelength gamma rays to produce a photon rocket.

The antiproton is much more suitable than the antielectron for propulsion systems. The annihilation of an antiproton by a proton (or neutron) does *not* produce gamma rays immediately; instead, the products of the annihilation are from 3 to 7 pions. On the average there are 3.2 charged pions and 1.6 neutral pions.[2] The neutral pions have a lifetime of only 90 attoseconds and almost immediately convert into two high-energy (200 MeV) gamma rays. The charged pions have a normal half-life of 26 ns. Because they are moving at 94% the speed of light however, their lives are lengthened to 70 ns. Thus, they travel an average of 21 m before they decay. This time and interaction length are easily long enough to collect the charged pions in a thrust chamber constructed of magnetic fields and direct the isotropic microexplosion into directed thrust. Even after the charged pions decay, they decay into energetic charged muons, which have even longer lifetimes and interaction lengths for further conversion into thrust. Thus, if sufficient quantities of antiprotons could be made, captured, and stored, then present known physical principles show that they can be used as a highly efficient propulsion fuel.

Because of the extreme difficulty in obtaining significant quantities of antimatter, the idea of an antimatter rocket has usually remained in the "science fiction" category. The literature prior to 1980 (see 27 references in section 02.01 of Ref. 3) was usually concerned with interstellar missions and glossed over the problems of generating, storing, and using the antimatter. Recent progress in particle physics on methods for obtaining intense antiproton beams, however, have caused those in the space propulsion community to take another look at the concept of antimatter propulsion to see if it can be removed from the "science fiction" category to the "engineeringly difficult and very costly" category, at which point the military services or NASA could begin considering its use. The last five years has seen the presentation of a number of papers on antimatter propulsion,[4-8] including a special issue of the *Journal of the British Interplanetary Society* on the subject of antimatter propulsion.[9-14]

The problems to be solved in making antiproton annihilation propulsion feasible can be listed as: antiproton generation, antiproton capture, cooling at relativistic velocities, deceleration from relativistic to subrelativistic velocities, cooling and slowing at subrelativistic velocities, conversion to antihydrogen, cooling and slowing of antihydrogen, conversion of antihydrogen atoms to antihydrogen molecules, cooling and slowing of molecular antihydrogen, stopping of antihydrogen molecules, trapping and cooling of antihydrogen molecules, conversion of antihydrogen gas to antihydrogen ice, long-term storage of antihydrogen ice, extraction of antihydrogen from storage, annihilation of antihydrogen, transfer of annihilation energy to working fluid, and conversion of working fluid energy to thrust.

Solutions to some of these problems, such as generation, capture, relativistic cooling, deceleration, and subrelativistic cooling have already been demonstrated. Solutions to the majority of the rest of the problems are in sight, although not all of them. The remainder of this paper will consider the present state-of-the-art, the problems yet to be solved, and how one might approach a solution to those problems.

Present Production Facilities

Antimatter in the form of antiprotons is being made and stored today, albeit in small quantities. The two major producers are the Institute for High Energy Physics (IHEP) in the USSR[15] and the Centre Européenne pour la Recherche Nucléaire, (CERN) in Europe.[16] In the U.S., Fermilab has started construction of their antiproton facility and expects to be in operation by 1985.[17] In these facilities, the antiprotons are generated by sending a high-energy beam of protons into a metal target. When the relativistic protons strike the dense metal nuclei, their kinetic energy, which is many times their rest-mass energy, is converted into a spray of particles, some of which are antiprotons. A magnetic field focuser and selector separates the antiprotons from the resulting debris and directs the antiprotons to a storage ring.

When the antiprotons are generated, they have a wide spread of energies. This makes it difficult to decelerate them

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to subrelativistic velocities, therefore, it is necessary to "cool" the beam so that all of the antiprotons have the same energy. Two techniques for reducing the velocity spread have been successfully demonstrated. In the stochastic cooling scheme,[18] the radio noise generated by fluctuations in the beam is detected. This noise is amplified, phase shifted, and then transmitted across the diameter of the ring to an electromagnetic kicker that suppresses the fluctuation. In the electron cooling scheme,[19] a beam of monoenergetic electrons is inserted into the ring with the antiprotons. Those antiprotons moving too slowly will be accelerated by electromagnetic interactions with the negative charge on the electrons and those moving too fast will be decelerated. These cooled antiprotons could then go through another stage of deceleration and cooling to bring them down to speeds suitable for capture, control, and cooling by other techniques. The acclerator at CERN generates 3.5 GeV antiprotons using a 26 GeV proton beam and has stored as many as 10^{12} antiprotons for days at a time in their magnetic ring "racetrack" antiproton accumulator.[20]

To give some scale as to what has already been accomplished at these research facilities, 10^{12} antiprotons have a mass of 1.7 pg. When this amount of antimatter is annihilated with an equivalent amount of normal matter, it will release 300 J, an engineeringly significant quantity of energy. To obtain this "firecracker" amount of annihilation energy required the use of multimillion-dollar machines that used an enormous amount of electric energy. Yet it is important to recognize that scientists working in basic physics, using research tools not designed for the job, have produced and continue to produce significant quantities of annihilation energy.

Present Production Rates

The capture efficiencies of the present antiproton facilities are abysmally low. The situation is summarized by Fig. 1 from Ref. 21. The upper part of the figure shows the total number of antiprotons generated per GeV of antiproton momentum per steradian of solid angle at the central portion of the antiproton beam. Integrating the curve over the antiproton momenta shows that each proton produces 7.7 antiprotons per steradian. The number of antiprotons per GeV of antiproton momentum for two different angular acceptances is shown in the lower two curves. In the paper, the number of antiprotons per GeV of antiproton momentum is estimated assuming that first antiproton collector at Fermilab can accept only those antiprotons with an angular spread off the axis of 30 mrad (0.0028 sr).

When the 30 mrad curve is integrated over the antiproton momenta a total of only 0.014 antiprotons power proton is found in this narrow angular acceptance. Then, of this small angular spread, the Fermilab collector is able to capture only those with a momentum (velocity) spread of 3% or 0.25 GeV around 8.9 GeV. Ideally, therefore, they would expect to capture about 1.8×10^{-4} antiprotons per proton, with an estimated actual capture rate (including mismatch and transport losses) of 3×10^{-5} antiprotons per proton. If the annihilation energy obtained from using the antiproton ($2m_0c^2 = 1.87$ GeV) is compared with the energy in the 120 GeV protons required to make that antiproton, an energy efficiency of 5×10^{-7} is attained. Since a typical synchrotron is only about 5% efficient, the "wall-plug" energy efficiency for antiproton production of present machines is only about 2×10^{-8}.

Future Production Rates

Data on the antiproton production spectrum of high-energy protons impacting heavy metal targets are available only for small angles about the forward direction. This data is sufficient for the design of the present antiproton collector systems that only attempt to capture the antiprotons emitted around the forward peak. In order to design systems that will capture a higher percentage of the antiprotons, it will be necessary to know the antiproton spectrum as a function of angle and incident proton energy over a greater angular spread. Such data does not seem to exist and there are no present plans to make these measurements, since obtaining the data would require an extensive amount of time on the large synchrotron machines. The particle physics community prefers to use the machine time to study more important issues to particle physics. As a result of this lack of detailed knowledge of the spectrum, the total number of antiprotons generated is also unknown (to probably a factor of 2).

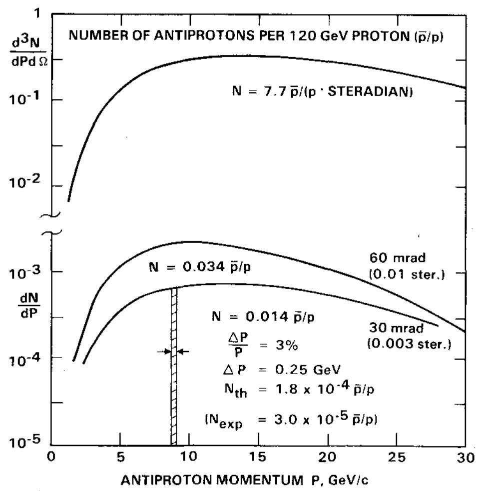

Fig. 1 Present antiproton capture efficiencies.

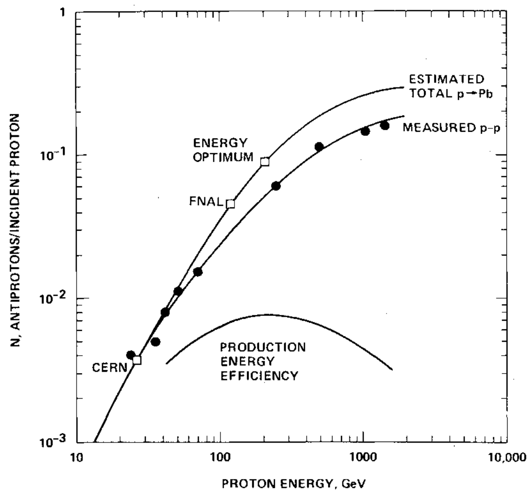

Fig. 2 Total antiproton production rates.

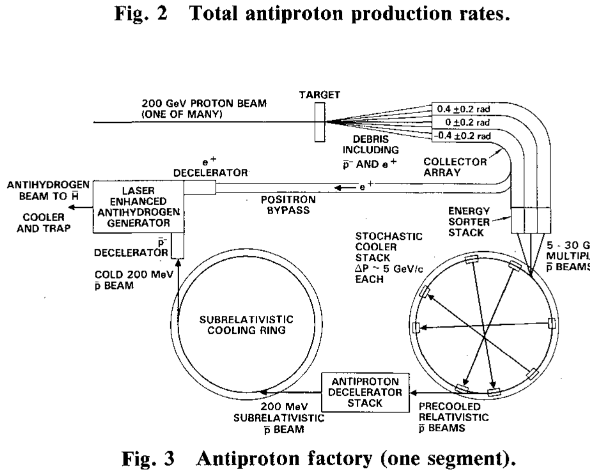

Fig. 3 Antiproton factory (one segment).

The last collection of experimental data on total antiproton production rates was done over a decade ago and published in a review paper by Antinucci et al.[22] The measurements were made using colliding beams of protons, therefore, the data is only partially relevant to the problem of colliding protons with heavy nuclei, which is known to give a higher antiproton production rate. The data from the table in Ref. 22 for the total antiproton production rate are the large dots in Fig. 2.

Using the known ratio of antiproton production in the forward direction from heavy nuclei and hydrogen targets,[21] the Antinucci hydrogen target data was modified to obtain the upper curve which gives the predicted antiproton production rates as a function of energy for protons incident on metal targets.

If we now take the upper curve, giving the number efficiency for producing antiprotons, and divide it by the energy of the proton making the antiprotons, we obtain the bottom curve. This is the energy efficiency for producing antiprotons. Note that it has a broad peak at approximately 200 GeV. Although the number of antiprotons produced continues to increase as the incident proton energy is increased, the gain in production above 200 GeV is not enough to offset the increased proton energy required.

It can be seen from Fig. 2 that the maximum energy efficiency production rate occurs for an incident proton energy of 200 GeV and is 0.085 antiprotons per proton. (There are roughly 5 K mesons, 50 pi mesons, and large numbers of positrons and electrons produced for each antiproton generated.) This antiproton production rate is 2 times the production at the Fermilab energy of 120 GeV and 20 times the production at the CERN energy of 26 GeV. It should be emphasized that the curves in Fig. 2 are based on sparse data and actual measurements of antiproton production spectra as a function of angle and proton energy are needed before any major engineering studies on antiproton production are done.

Antiproton Factory

Figure 3 presents a conceptual design for an antiproton factory which would utilize the technologies being developed at CERN, Fermilab, and IHEP, but on a much larger scale and with the design optimized for energy efficiency. First, the proton accelerator should be a high current radio-frequency (rf) linear accelerator (linac) with a wall-plug efficiency of 50%, rather than the low-current, low-efficiency, but high-energy resolution synchrotron preferred as a research tool by particle physicists. There would be more than one proton beam with each beam operated at the optimum beam current for the particular target design chosen. Each proton beam would strike a metal target and the resulting particles would be sorted by an array of wide-angle collecting lenses to extract the antiprotons and positrons. The positrons with the right energy would be picked off and sent to the antihydrogen generator, while all of the antiprotons possible would be sorted by energy and sent to a stack of stochastic coolers, each optimized for a particular central antiproton momentum.

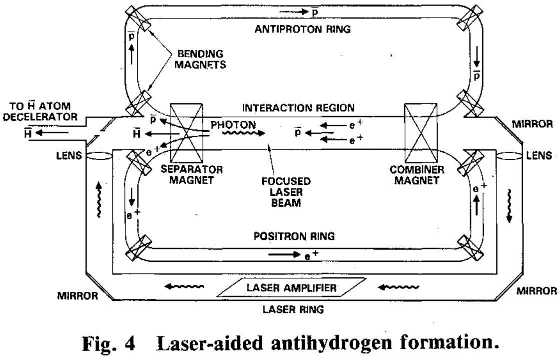

Fig. 4 Laser-aided antihydrogen formation.

After stochastic cooling, the stack of beams at different energies would go to a decelerator stack that would reduce all of the antiproton energies to the same subrelativistic energy (200 MeV). The combined beam would then be sent to a subrelativistic cooling ring using either stochastic or electron cooling before being decelerated further and sent on to the antihydrogen generator where the antiprotons are combined with the positrons to make antihydrogen atoms.

Antihydrogen

The antihydrogen generator would follow the general concepts described in a recent research publication at CERN.[23] As is shown in Fig. 4, if a beam of positrons is traveling at the same speed with a beam of antiprotons, they will attract one another and recombine to form antihydrogen. This natural process can be enhanced by factors of 100 or more by stimulating the capture process with photons at the right wavelength.

Once an antihydrogen beam has been formed, there are a number of techniques available for cooling the electrically neutral antihydrogen down, slowing it to a stop, and storing it in a trap. Traps for atoms were first proposed by Letokov and Minogin[24] and Ashkin and Gordon.[25] These traps use laser beams tuned just below the first optical resonance line of the atom. Those atoms trying to move toward the laser will see the laser photons shifted upward into resonance with optical absorption line. The atoms will absorb the Doppler-shifted laser photons, slowing down slightly in the process. The atom then reradiates each photon, but in a random direction, therefore, the recoils from the reradiated photons will average out. Thus, after many absorptions and reradiations, the atom has stopped moving. Once the atom is stationary, it no longer absorbs the off-resonant laser photons and stays trapped.

Lasers have also been used to "push" a beam of sodium atoms to one side, "cool" the beam both longitudinally and transversely until all of the atoms have the same speed, and slow down, halt, and reverse the direction of an atomic beam. The activities in the field of cooling and trapping atoms have progressed to the point where there are periodic workshops on laser cooling and trapping.[26]

Although it might be possible to store antihydrogen as an atomic gas,[27] the atomic form of antihydrogen is more difficult to control, cool, and trap than sodium, since the first resonance line in atomic hydrogen is in the vacuum ultraviolet (the Lyman alpha line). The fundamental problem is that while one Lyman alpha photon will excite an antihydrogen atom, if a second photon arrives before the atom has decayed back into its ground state, the second photon may ionize the antihydrogen atom. Although proprietary ideas exist for overcoming these problems, it is likely that it will be found necessary to convert the antihydrogen atoms into antihydrogen molecules, then store them as antihydrogen ice. The conversion of antihydrogen atoms to antihydrogen molecules takes place naturally (with the release of a great amount of energy, which is why spin-polarized normal hydrogen is being looked at as a potential rocket fuel). However, a large number of the molecules are left in a metastable orthohydrogen state. Left to itself, all of the cold antihydrogen molecules ultimately will convert to parahydrogen, the ground state of the molecule. Unless a catalyst is used, however, the process takes many days. Research is needed on the use of lasers and magnetic fields with high gradients to convert the antihydrogen atoms into antihydrogen molecules in the ground state. These antihydrogen molecules can then be further cooled and trapped using lasers operating on a molecular hydrogen line, then turned into antihydrogen ice in the preferred parahydrogen state. Research is also needed on turning a cold antihydrogen vapor into ice crystals, since there is a heat of fusion generated during the formation of the ice. Fortunately, all of these research problems on manipulation of antihydrogen can be studied using normal hydrogen (and would make excellent thesis topics).

Antihydrogen Traps

Antihydrogen ice, like hydrogen ice, is diamagnetic, with a negative magnetic susceptibility that is two-thirds that of graphite. A simple passive trap for a ball of antihydrogen ice could be made of magnetic fields. There are a number of different ways to configure permanent magnets and coils to produce a magnetic field minimum that will attract and trap a diamagnetic material such as graphite[28] or hydrogen. One simple example consists of two superconducting coils spaced so that there is a magnetic minimum midway between them.[29] This type of trap would be completely stable and require no power. However, it is not very deep, and, although quite suitable for storage of antihydrogen ice in free fall, it might not be able to levitate the antihydrogen ice at high acceleration levels.

For high acceleration levels, a more suitable trap would be a servo-controlled dc voltage electrostatic levitation mechanism such as those made at Jet Propulsion Laboratory.[30] These traps have levitated electrically charged millimeter-sized 20-mg spheres of water ice in the Earth's field. Antihydrogen ice will have a density of 0.0763 g/cm^3, which is 13 times less than water ice. Thus, the same electrostatic suspension could hold milligram-sized balls of antihydrogen ice at accelerations up to 13 *g*. Since the antihydrogen ice will be formed at mK or below, and the heat input from the electric levitator will be low, the sublimation pressure of the antihydrogen will be so low (10^{-39} Torr at 1 K) that the antihydrogen ice ball should last for years.

Utilizing Antihydrogen for Propulsion

There are a number of techniques for extracting the antihydrogen from the storage trap and directing it into the rocket engine under control. If the antihydrogen is in the form of a large ball many milligrams in size, then the antiprotons can be extracted from the ice ball by irradiating the ice with ultraviolet, driving off the positrons, extracting the excess antiprotons by field emission with a high-intensity electric field, and then directing them to the thrust chamber.[12] It might be more desirable if the antihydrogen could be formed as a cloud of charged microcrystals, each a microgram and containing the energy equivalent of 20 kg of chemical fuel. Then, using a directed beam of ultraviolet light to drive off a few more positrons, an individual microcrystal could be made more highly charged, preferentially extracted from the microcrystal cloud using electric fields, and directed down a vacuum line to the thrust chamber. Since the position of the charged microcrystal in the injection line can be sensed, mechanical shutters can allow the passage of the microcrystal without breaking the vacuum.

Antimatter fuel is so powerful that new types of rocket engines will have to be developed to fully utilize its potential. One of the simplest antiproton propulsion systems would use a design similar to that of a nuclear thermal rocket. In a nuclear thermal rocket, hydrogen gas is heated by passing it through the core of a fission reactor. The hot hydrogen is then used to provide thrust. In the antiproton annihilation version, the energy released by the annihilation reaction would be absorbed in the walls of a heat exchanger made out of refractory metal. The heat exhanger would then heat hydrogen to produce thrust.[31] A heat exchanger made out of a cylinder of tungsten 28 cm in diameter and 28 cm long would only weigh 330 kg and capture most of the energy in the gamma rays and pions emitted by the antiproton-proton annihilation process, thus utilizing all of the energy in the annihilation reaction. The maximum temperature would be limited by the melting point of tungsten to about 3000 K, resulting in a maximum specific impulse of about 900 s or an exhaust velocity of about 9 km/s. This is considerably better than any chemical rocket or even a nuclear fission thermal rocket, but still does not use the high exhaust velocity potential of antiproton annihilation.

The plasma created by the heating of the hydrogen working fluid by the pions emitted by the annihilation process is too hot to be contained and directed by thrust chambers and nozzles made of solid material. Fortunately, most of the particles generated are charged and can be contained and directed by strong magnetic fields. The first example of a design for a magnetic field antiproton rocket engine can be found in Ref. 12.

Minimum Antimatter Optimization

When antiprotons interact with protons (hydrogen), the resultant annihilation products are pions with an average kinetic energy of 250 MeV. This translates into an exhaust velocity of 94% of the speed of light. Thus, pure antimatter rockets are best suited for relativistic missions. In order to use the minimum amount of antimatter for the mission, the best way to use the antimatter is *not* to use equal amounts of matter and antimatter. Instead, the antimatter should be used to heat a much larger amount of propellant. It has been shown,[32] that, except for extreme relativistic spacecraft speeds ($>0.5c$), the reaction mass needed is always four times the spacecraft payload mass, or an overall ratio of launch mass to payload mass of 5:1. The mass of the antimatter needed increases as the square of the mission total velocity change, but is always a negligible fraction of the total mass. Because the mass ratio of an antimatter-powered space vehicle will always be less than 5:1 (typically 2-3:1), mission analysts need to rethink those missions that have been labeled "impossible" due to the extreme mass ratios required to accomplish the mission using a chemical or nuclear system with a fixed specific impulse.

Antimatter-Powered Mission Analyses

In some preliminary studies of an antihydrogen/hydrogen rocket, Cassenti[6] has estimated some of the parameters in an antimatter-powered orbit transfer mission. The mission was to take a 10-ton spacecraft from LEO to GEO back to LEO (using aeroassist). The mission velocity change was assumed to be 5.5 km/s. Using the minimum antimatter optimization, Cassenti found that the optimum exhaust velocity was 3.4 km/s (specific impulse of only 350 s), the reaction mass required was 40 tons, and the amount of antihydrogen needed was only 6 mg. If the amount of antihydrogen used is raised from 6 to 10 mg, then the amount of hydrogen reaction mass drops dramatically, from 40 to 15 tons, giving a mass ratio of 2.5:1, while the exhaust velocity rose to 5 km/s. Thus, in this range of the parameters, an additional 4 mg of antihydrogen saves 25 tons of reaction mass. Whether this tradeoff is beneficial depends upon the relative cost of antihydrogen per milligram compared to the cost of hydrogen per ton in LEO. In a recently completed study[33] it was estimated that a well-designed factory for producing antihydrogen should be able to operate at an energy efficiency of better than 10^{-4} (compared to the present efficiency of 2×10^{-8}). The cost of the antimatter was estimated to be about $10M per milligram, while reaction mass in LEO was estimated to cost $5M per ton. Thus, using the numbers from Ref. 6, an additional 4 mg ($40M) of antimatter fuel in the rocket saved 25 tons ($125M) of reaction mass. Although these cost estimates are far from firm, it looks as though antimatter might be a cost-effective fuel for space propulsion.

Conclusions

It is concluded that the antiproton propulsion concept presented herein is feasible but difficult and expensive. Yet, despite the high cost of antimatter, it may be a cost-effective fuel in space where any fuel is expensive. There is high risk in the development of antiproton propulsion. The major uncertainties seem to be in the production and capture of the antiprotons at high efficiency, and the conversion of antiprotons into frozen antihydrogen without excessive losses. The storage problems look tractable. The problems that need to be solved first are to determine the total antiproton production rate and spectrum vs proton energy, the maximum feasible limits to antiproton capture efficiencies of physically feasible lenses and accumulator rings, and the maximum efficiency of the antimatter rocket that uses the antiproton fuel. It is important to recognize that many of the problems of capturing, cooling, slowing, trapping, and storing antiprotons (antihydrogen) can be done as thesis topics using normal protons and hydrogen.

Acknowledgment

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References

[1]Sänger, E., "The Theory of Photon Pockets," *Ingenieur Archiv,* Vol. 21, 1953, pp. 213 ff.

[2]Agnew, L. E. et al., "Antiproton Interactions in Hydrogen and Carbon Below 200 MeV," *Physical Review*, Vol. 118, June 1960, pp. 1371 ff.

[3]Mallove, E. F., Forward, R. L., Paprotny, Z., and Lehmann, J., "Interstellar Travel and Communication: A Bibliography," *Journal of the British Interplanetary Society*, Vol. 33, June 1980, pp. 201-248.

[4]Forward, R. L., "Interstellar Flight Systems," AIAA Paper 80-0823, May 1980.

[5]Cassenti, B. N., "Antimatter Propulsion for OTV Applications," AIAA Paper 84-1485, June 1984.

[6]Cassenti, B. N., "Optimization of Relativistic Antimatter Rockets," *Journal of the British Interplanetary Society*, Vol. 37, Nov. 1984, pp. 483-490.

[7]Vulpetti, G., "A Propulsion-Oriented Synthesis of the Antiproton-Nucleon Annihilation Experimental Results," *Journal of the British Interplanetary Society*, Vol. 37, March 1984, pp. 124-134.

[8]Vulpetti, G., "An Approach to the Modeling of Matter-Antimatter Propulsion Systems," *Journal of the British Interplanetary Society*, Vol. 37, Sept. 1984, pp. 403-409.

[9]Massier, P. F., "The Need for Expanded Exploration of Matter-Antimatter Annihilation for Propulsion Application," *Journal of the British Interplanetary Society*, Vol. 35, Sept. 1982, pp. 387-390.

[10]Forward, R. L., "Antimatter Propulsion," *Journal of the British Interplanetary Society*, Vol. 35, Sept. 1982, pp. 391-395.

[11]Cassenti, B. N., "Design Considerations for Relativistic Antimatter Rockets," *Journal of the British Interplanetary Society*, Vol. 35, Sept. 1982, pp. 396-404.

[12]Morgan, D. L., "Concepts for the Design of an Antimatter Annihilation Rocket," *Journal of the British Interplanetary Society*, Vol. 35, Sept. 1982, pp. 405-412.

[13]Zito, R. R., "The Cryogenic Confinement of Antiprotons for Space Propulsion Systems," *Journal of the British Interplanetary Society*, Vol. 35, Sept. 1982, pp. 414-421.

[14]Chapline, G., "Antimatter Breeders?," *Journal of the British Interplanetary Society*, Vol. 35, Sept. 1982, pp. 423-424.

[15]Vsevolozskaya, T. A. et al., "Antiproton Source for the Accelerator-Storage Complex, UNK-IHEP," Fermilab Report FN-353 8000.00, June 1981, a translation of INP Preprint 80-182, Dec. 1980.

[16]"The CERN PS Complex as an Antiproton Source," *IEEE Transactions on Nuclear Science*, Vol. NS-30, Aug. 1983, pp. 2039-2041.

[17]Peoples, J., "The Fermilab Antiproton Source," *IEEE Transactions on Nuclear Science*, Vol. NS-30, Aug. 1983, pp. 1970-1975.

[18]Van der Meer, S., "Stochastic Cooling in the CERN Antiproton Accumulator," *IEEE Transactions on Nuclear Science*, Vol. NS-28, June 1981, pp. 1994-1998.

[19]Bell, M., Chaney, J., Herr, H., Krienen, F., Møller-Petersen, P., and Petrucci, G., "Electron Cooling in ICE at CERN," *Nuclear Instrumentation and Methods*, Vol. 190, Feb. 1981, pp. 237-255.

[20]Cline, D. B., Rubbia, C., and Van der Meer, S., "The Search for Intermediate Vector Bosons," *Scientific American*, Vol. 247, March 1982, pp. 48-59.

[21]Hojvat, C. and Van Ginneken, A., "Calculation of Antiproton Yields for the Fermilab Antiproton Source," *Nuclear Instrumentation and Methods*, Vol. 206, Jan. 1983, pp. 67-83.

[22]Antinucci, M. et al., "Multiplicities of Charged Particles up to ISR Energies," *Letters Nuovo Cimento*, Vol. 6, Jan. 1973, pp. 121-127.

[23]Neumann, R., Poth, H., Winnacker, A., and Wolf, A., "Laser-Enhanced Electron-Ion Capture and Antihydrogen Formation," *Zeitschrift für* Physik A, Vol. 313, March 1983, pp. 253-262.

[24]Letokhov, V. S. and Minogin, V. G., "Laser Radiation Pressure on Free Atoms," *Physics Reports*, Vol. 73, Jan. 1981, pp. 1-65 (review).

[25]Ashkin, A. and Gordon, J. P., "Cooling and Trapping of Atoms by Resonance Radiation Pressure," *Optics Letters*, Vol. 4, June 1979, pp. 161-163.

[26]Phillips, W. D., ed., "Laser-Cooled and Trapped Atoms," *Proceedings of Workshop on Spectroscopic Applications of Slow Atomic Beams,* NBS, Gaithersburg, Md., NBS Special Pub. 653, April 1983.

[27]Cline, R. W., Smith, D. A., Greytak, T. J., and Kleppner, D., "Magnetic Confinement of Spin-Polarized Atomic Hydrogen," *Physical Review Letters*, Vol. 45, 29 Dec. 1980, pp. 2117-2120.

[28]Waldron, R. D., "Diamagnetic Levitation Using Pyrolytic Graphite," *Reviews of Scientific Instruments*, Vol. 37, Jan. 1966, pp. 29-34.

[29]Letokhov, V. S. and Minogin, V. G., "Possibility of Accumulation and Storage of Cold Atoms in Magnetic Traps," *Optics Communications*, Vol. 35, Nov. 1980, pp. 199-202.

[30]Rhim, W.-K., Saffren, M. M., and Elleman, D. D., "Development of Electrostatic Levitator at JPL," *Materials Processing in the Reduced Gravity Environment of Space*, edited by G. E. Rindone, Elsevier Science, 1982, pp. 115-119.

[31]Augenstein, B., private communication, Rand Corp., Santa Monica, California.

[32]Shepherd, L. R., "Interstellar Flight," *Journal of the British Interplanetary Society*, Vol. 11, July 1952, pp. 149-167.

[33]Forward, R. L., "Alternate Propulsion Energy Sources," AFRPL-TR-83-067, Dec. 1983. (Distribution limited to U.S. government agencies and DOD contractors.)