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for the period
1 May 1986 to
30 June 1987

Advanced Space Propulsion Study
Antiproton and Beamed Power Propulsion

October 1987

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FOREWORD

This final report was prepared by Hughes Research Laboratories in completion of contract F04611-86-C-0039 with the Air Force Astronautics Laboratory (AFAL), Edwards Air Force Base, CA. The period of the report is 1 May 1986 to 30 Jun 1987. AFAL Project Manager was Dr Frank Mead.

This technical report has been reviewed and is approved for distribution in accordance with the the distribution statement on the cover and on the DD Form 1473.

Franklin B. Mead Jr.

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FOR THE COMMANDER

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The contract objective was to monitor the research at the forefront of physics and engineering to discover new spacecraft propulsion concepts. The major topics covered were antiproton annihilation propulsion, laser thermal propulsion, laser-pushed lightsails, tether transportation systems, solar sails, and metallic hydrogen. Five papers were prepared and are included as appendices. They covered (1) pellet, microwave, and laser beamed power systems for interstellar transport; (2) a design for a near-relativistic laser-pushed lightsail using near-term laser technology; (3) a survey of laser thermal propulsion, tether transportation systems, antiproton annihilation propulsion, exotic applications of solar sails, and laser-pushed interstellar lightsails; (4) the status of antiproton annihilation propulsion as of 1986, and (5) the prospects for obtaining antimatter ions heavier than antiprotons. Two additional appendices contain the first seven issues of the Mirror Matter Newsletter concerning the science and technology of antimatter, and an annotated bibliography of antiproton science and technology.

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INTRODUCTION AND SUMMARY

The objective of this contract was to monitor the research at the forefront of physics and engineering in order to discover new technology and scientific phenomena that might have application to spacecraft propulsion; and based on these latest developments, to propose new spacecraft propulsion concepts. The effort was to include an emphasis on the study of antiproton annihilation propulsion and to present approaches for promoting the scientific and technology issues of this concept.

During the contract a series of separate studies on possible advanced space propulsion concepts were carried out. Some of these studies were successful in adding to the knowledge about present propulsion concepts or in inventing new space propulsion concepts. Other studies were unproductive and were dropped. The successful studies resulted in a number of written reports and briefings, as well as five papers prepared for presentation and publication in the proceedings of meetings or in scientific journals.

The first paper (reprinted in Appendix A), "Beamed Power Propulsion to the Stars," was presented at the AAAS Symposium on Interstellar Communication and Travel at the AAAS Annual Meeting, held in Philadelphia, Pennsylvania (25-30 May 1986). The paper will be published in a forthcoming AAAS Symposium Proceedings. In the paper I discuss three different beamed power propulsion systems capable of achieving the very difficult advanced space propulsion mission of sending payloads over interstellar distances. The three systems are pellet-stream-pushed, microwave-beam-pushed, and laser-beam-pushed. The presentation also resulted in a large number of newspaper feature articles, and radio and television interviews that brought the subject of advanced propulsion to the attention of the general public.

The second paper (reprinted in Appendix B), "Laser Weapon Target Practice with Gee-Whiz Targets," was contributed to the Laser Propulsion Workshop held at Lawrence Livermore National

Laboratory, Livermore, California (7-18 July 1986). The paper will appear in a forthcoming workshop proceedings. In the paper I discuss a new concept for a very high performance laser-pushed lightsail that uses near-term high power laser systems to boost very light payloads to terminal velocities approaching 0.01 c.

The third paper (reprinted in Appendix C), "Exotic Propulsion in the 21st Century," was an invited keynote paper at the 21st Century Space Propulsion session of the American Astronautical Society 33rd Annual Meeting held in Boulder, Colorado (26-29 October 1986). This paper is available as AAS Preprint 86-409. In the paper I review laser thermal propulsion, tether transportation systems, antiproton annihilation propulsion, exotic missions using solar sails, and laser-pushed lightsails for interstellar transport.

The fourth paper (reprinted in Appendix D), "Prospects for Antiproton Production and Propulsion," was an invited keynote paper at the Cooling, Condensation, and Storage of Hydrogen Cluster Ions Workshop held at SRI International, Menlo Park, California (8-9 January 1987). The paper will appear in the workshop proceedings. In the paper I review the past history of antiproton annihilation propulsion for the workshop attendees and point out the critical areas of antihydrogen storage technology they needed to address in their workshop.

The fifth paper (reprinted in Appendix E), "Production of Heavy Antinuclei: Review of Experimental Results," dated 23 April 1987, was prepared as a result of a question raised at the Hydrogen Cluster Ions Workshop concerning the possible availability to cluster ion researchers of heavier antimatter ions than antiproton ions, for possible use in nucleating or stabilizing antihydrogen ion clusters. In the paper I survey the past literature on the production of heavier antimatter ions and predict that small amounts of antideuterium, antitritium, and antihelium-3 ions might be available using present antiproton production facilities. Heavier ions like antihelium-4 and antilithium will probably require the construction of special facilities to fabricate the heavier ions from fusion of antideuterium and antitritium. The paper will appear in the proceedings of both the Cooling, Condensation, and Storage of Hydrogen Cluster Ions Workshop held at SRI International, Menlo Park, California (8-9 January 1987), and the Antiproton Science and Technology Workshop held at RAND Corporation, Santa Monica, California (21-22 April 1987).

In order to promote the science and technology of antiproton annihilation propulsion, seven issues of an informative newsletter on antimatter science and technology, called the Mirror Matter Newsletter, were prepared and distributed to over 500 scientists and engineers. The news portions of the Mirror Matter Newsletter are included as Appendix F.

The Mirror Matter Newsletter also contained updates to a previously compiled and published bibliography on antimatter science and technology. The complete bibliography including the past entries and the update entries from the Mirror Matter Newsletter were combined into a single annotated bibliography, which is included as Appendix G.

ANTIPROTON ANNIHILATION PROPULSION

A major new form of propulsion has just graduated from the never-never land of science fiction and has now become a serious topic for scientific and engineering investigation. In the past it was called antimatter propulsion, but to emphasize the difference between past fiction and present reality, I prefer to call it antiproton annihilation propulsion,[1] for the use of antiprotons as the form of the antimatter is crucial to the use of antimatter for propulsion.

PROPERTIES OF ANTIMATTER

For every particle known to exist, there is a mirror image twin particle that has its charge, spin, and quantum states reversed from that of normal particles. As shown in Figure 1, the stable particles that make up atoms--electrons, protons, and neutrons--have mirror twins called positrons, antiprotons, and antineutrons. Conceptually, these could be combined to form antiatoms, such as antihydrogen.

When a particle comes near its antiparticle, they attract each other and annihilate each other, totally converting all of their rest mass into energy. When positrons and electrons annihilate they produce gamma rays, which are difficult to convert to thrust. On the contrary, when antiprotons annihilate with protons, the annihilation process does <u>NOT</u> produce gamma rays immediately. Instead, the products of the annihilation are from three to seven particles called pions. On the average there are three charged pions and two neutral pions. The neutral pions have a very short lifetime and almost immediately convert into two high energy gamma rays. The charged pions have a normal half-life of 26 ns. Because they are moving at 94% of the speed of light, however, their lives are lengthened to 70 ns. Thus, they travel an average of 21 m before they decay. These charged pions contain 60% of the annihilation energy.

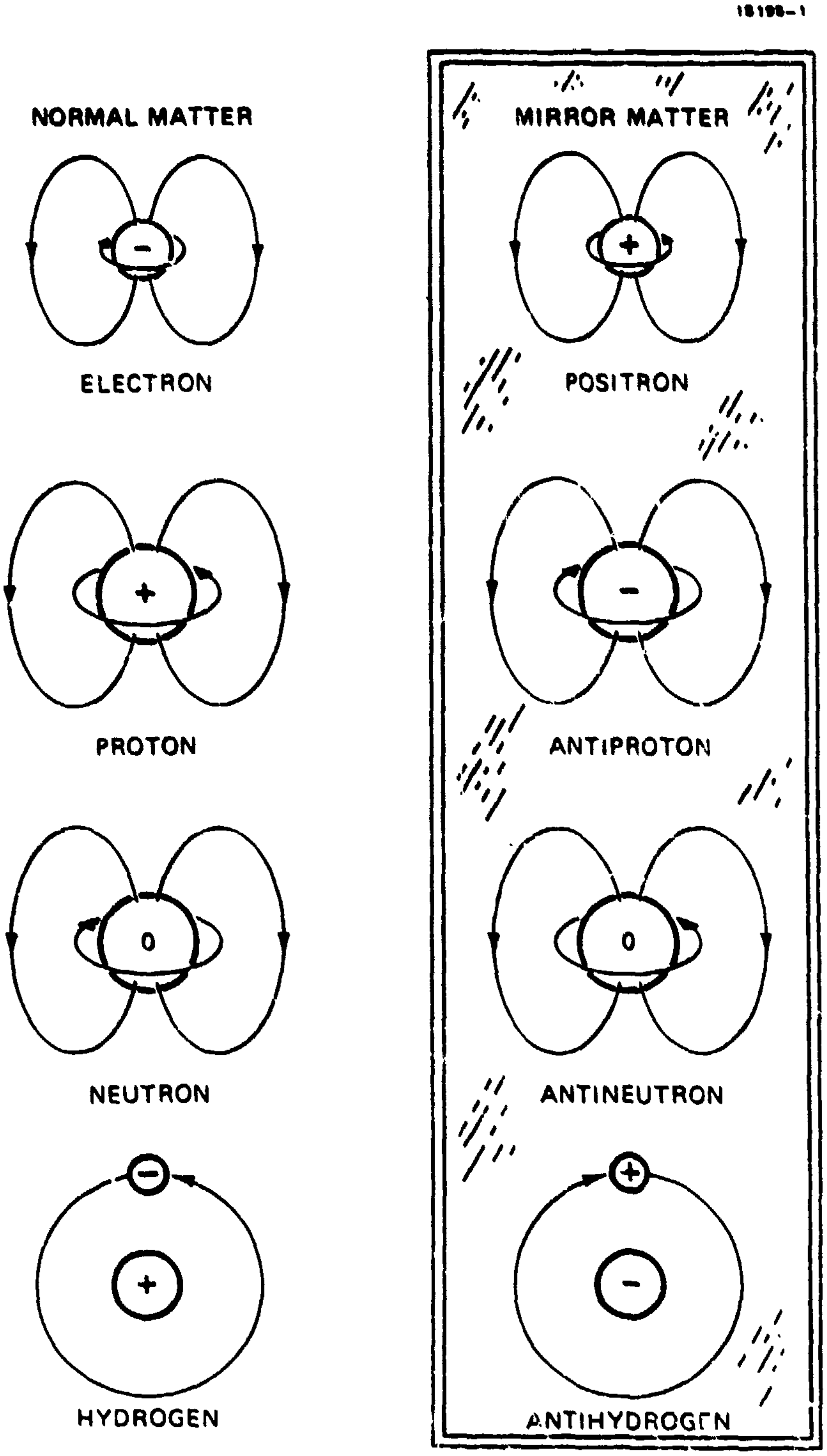

Figure 1. Normal matter and mirror matter.

APPLICATION TO PROPULSION

Because of the long lifetime and interaction length of the charged pions that result from the annihilation of antiprotons with protons, it is relativly easy to collect the charged pions in a thrust chamber constructed of magnetic fields and to obtain propulsion from them. As is shown in Figure 2, the energy in the pions can then either be used to heat a working fluid, such as hydrogen, to produce thrust, or the high speed pions themselves can be directed by a magnetic nozzle to produce 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 presently known physical principles show that they can be used as a highly efficient propulsion fuel.[1]

Since antimatter does not exist naturally, it must be made, one particle at a time. It is a synthetic fuel. It will always require much (~10^4 times) more energy to produce antimatter than can be extracted from the annihilation process. Its major

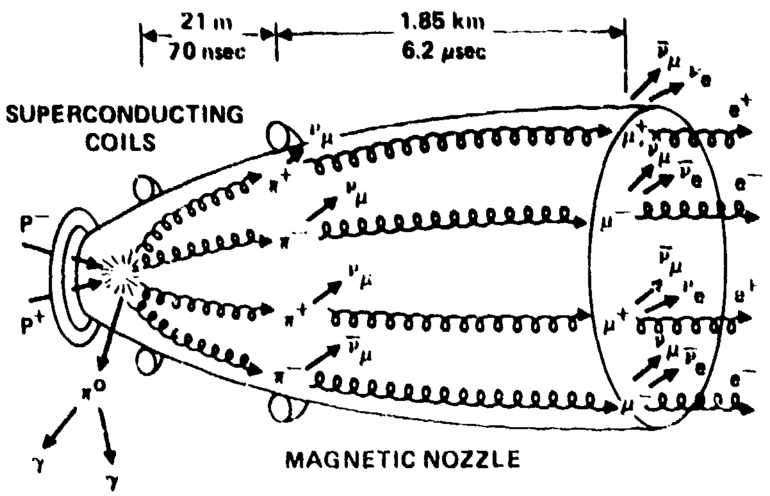

Figure 2. Schematic of antiproton annihilation propulsion.

advantage is that it is a highly concentrated form of energy storage. A tenth of a milligram, about the size of a single grain of salt, contains the energy of 2 tonnes of the best rocket fuel known, liquid oxygen/liquid hydrogen. A study that compared antihydrogen propulsion systems with chemical propulsion systems[2] found that antiproton propulsion could possibly be cost effective for space propulsion. More importantly, it was mission enabling, in that it would allow missions to be performed that are essentially impossible to perform with chemical fuels.

MAKING ANTIPROTONS

Antimatter in the form of antiprotons is being made today, albeit in small quantities. As is shown in Figure 3, 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 into a storage ring. These

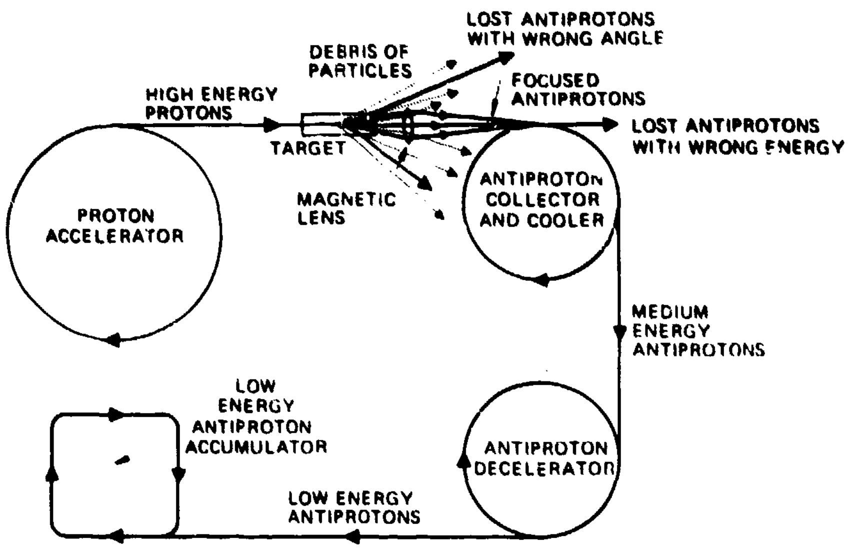

Figure 3. Present method of making antiprotons.

collecting rings have stored as many as 10^{12} antiprotons for days at a time. 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 amount of energy.

STORING ANTIMATTER

In a recent experiment,[3] a team of scientists took the low energy antiprotons in one of these rings, slowed them down to almost zero velocity, and captured a few hundred antiprotons in a small electromagnetic ion trap. Other experiments planned for late 1987 will attempt to capture many millions of antiprotons in a trap no bigger than a thermos bottle. The electromagnetic trap will be made portable so the antiprotons can be transported to other laboratories for experiments.

In order to use antiprotons as a propulsion fuel, it will be necessary to find a more compact method of storage than an ion trap, which is limited to relatively low ion densities. Another Air Force sponsored research program is looking into adding positrons to the antiprotons in the ion traps and slowly building up "cluster ions" of antihydrogen. These cluster ions are large agglomerations of neutral antihydrogen atoms clustered around a single antiproton ion. The net negative electric charge of the cluster ion allows it to be kept in the ion trap, yet the mass of each ion can be increased until we have an ice crystal with enough charge that it can be electrostatically levitated without touching the walls of the cryogenically cooled trap.

ANTIMATTER ENGINES

The use of antihydrogen to power antimatter engines is fairly straightforward. The small antihydrogen microcrystals, each weighing about a microgram and having the energy content of 20 kg of LOX/hydrogen, would be extracted electromagnetically from the storage trap, directed by electric fields down a vacuum line with shutters (to maintain the trap vacuum), then electrostatically ejected with a carefully selected velocity into the rocket chamber, where the antiprotons would annihilate with the reaction fluid, heating it up to provide high thrust at high specific impulse. The annihilation cross section increases dramatically at low relative velocity, so the annihilation process occurs mostly at the center of the chamber.

Designs of rocket engines to use antimatter are well underway at a number of engineering laboratories. One simple design[4] is based on the NERVA nuclear rocket, with the nuclear reactor replaced with a tungsten heat exchanger core. The reaction products (both gammas and pions) would be stopped in the tungsten and the energy used to heat hydrogen gas passing though the heat exchanger. This engine would use 13 μg/s of antiproton fuel to produce a specific impulse of 1100 s at a thrust level of 4.4×10^5 N (100,000 lb) for a power level of 2.7 GW. Such an engine could take 100 tonnes of payload to Mars and back in six months (only three months each way) with a mass ratio of 4. By comparison, a LOX/hydrogen system would require a mass ratio of 13 and would take 12 months to get there and 9 months to get back.

Studies have also started on magnetic bottle reaction chambers[5] that have the potential of attaining higher specific impulse than engines limited by the thermal properties of matter. Analysis of plasma transport coefficients has identified two parameter regimes of practically lossless operation of a magnetic nozzle with a pure hydrogen plasma. The one of interest for an antimatter-heated hydrogen plasma thruster is optically thick, with a density of 3×10^{19} ions/cm^3, a temperature of 2 eV (23,000K), a magnetic field of 5 T, a throat dimension of 1 m, and a pressure of 1000 psi (67 atm).

FUTURE PLANS FOR ANTIPROTON ANNIHILATION PROPULSION

Because antiproton propulsion promises a major advance in space propulsion capability, the recently completed Air Force Systems Command Project Forecast II study recommended that the Air Force start a new program in antimatter propulsion. As a direct result of the Project Forecast II recommendations, the Air Force Astronautics Laboratory at Edwards AFB in California has reorganized its advanced propulsion activities and formed a new project called ARIES (Applied Research In Energy Storage). The project has two major thrusts - chemically bound excited states and antimatter. The Air Force Office of Scientific Research has initiated a new program on antimatter research in the Physical and Geophysical Sciences Branch under Col. Hugo Weichel. The Program Manager for Antimatter is Maj. John Prince, who evaluates unsolicited proposals for research on antimatter sciences. In Europe, an Antimatter Research Team (ART) has been formed at Telespazio, SpA per le Comumicazioni Spaziali in Italy. Their research work[6] will cover antiproton and positron production and storage, and engine simulations, leading ultimately to technology demonstrations.

The number of workshops concerned with the science and technology of antiprotons is growing with each passing year. I have been involved in one way or another with most of the following workshops. The Workshop on the Design of a Low Energy Antimatter Facility in the USA was held at the University of Wisconsin-Madison from 3-5 October 1985. The Antimatter Physics at Low Energy Workshop was held at Fermi National Accelerator Laboratory, Batavia, Illinois from 10-12 April 1986. The AGS Time-Separated Antiproton Beam Workshop was held at Brookhaven National Laboratory, Upton, New York from 18-22 August 1986. The Cooling, Condensation, and Storage of Hydrogen Cluster Ions Workshop was held at SRI International, Menlo Park, California from 8-9 January 1987. The Antiproton Science and Technology Workshop was held at RAND Corporation from 21-22 April 1987. The

Workshop on Intense Positron Beams was held at Idaho National Engineering Laboratory, Idaho Falls, Idaho from 18-19 June 1987. Additional planned workshops will be the IV LEAR (Low Energy Antiproton Ring) Workshop to be held in Villars, Switzerland from 6-13 September 1987, and the 2nd Antiproton Science and Technology Workshop to be held at RAND Corporation, Santa Monica, California from 6-8 October 1987.

If the next decade of experimental research on cooling and trapping of antiprotons, the growth and storage of antihydrogen, and the design studies of antimatter rockets and antimatter-powered missions shows promise, then engineering studies will commence on the design and ultimate fabrication of an antiproton factory capable of producing about a microgram a year (compared to the present nanogram per year). A microgram of antiprotons with usable energy of 100 MJ could power a test stand run of a 1 MW feasibility demonstration rocket engine for 100 s. At that point a lot more would be known about the engineering feasibility, cost effectiveness, and desirability of antiproton annihilation propulsion. Then a decision could be made whether to proceed with the construction of an antiproton factory that could produce the hundreds of milligrams a year needed to run a space program. Such a factory could be designed to be self-powering, but would require a capital investment comparable to building a 10 GW power plant.

BEAMED POWER PROPULSION

It is not necessary to use the rocket principle to build a vehicle that can travel through space. If we examine the components of a generic rocket, we find that it consists of payload, structure, propellant, energy source, an engine to put the energy into the propellant, and a thruster to expel the energized propellant to provide thrust. In most rockets, the propellant and energy source are combined together into the chemical "fuel." Because a standard rocket has to carry its fuel along with it, its performance is significantly limited. For a mission where the final vehicle velocity increment needed is ΔV, and the propellant exhaust velocity is v, the mass of fuel m_f needed to propel a vehicle of mass m_v rises exponentially with the ratio $\Delta V/v$:

$$m_f = m_v(e^{\Delta V/v}-1) \quad .$$

If one attempts to do a difficult mission, such as a Saturn ring rendezvous mission, where the required mission ΔV is 48 km/s, using even our best chemical rocket, a liquid oxygen/liquid hydrogen system with a propellant exhaust velocity v of 5 km/s, then $\Delta V/v$ is 9.6, and $(e^{\Delta V/v}-1) = 15{,}000$. It is not possible to build a spaceship that holds 15,000 times as much fuel mass as vehicle mass.

There is a whole class of spacecraft that do not have to carry along any energy source or propellant or even an engine, and consist only of payload, structure, and thruster. These spacecraft work by beamed power propulsion. In a beamed power propulsion system, the heavy parts of a rocket (propellant, energy source, and engine) are left on the ground or in orbit, while the payload and associated structure carry out the mission. Essentially unlimited amounts of propellant and energy can be supplied to carry out the mission, and the engine can be maintained and even upgraded as the mission proceeds.

Many examples of beamed power propulsion systems have been discussed in the literature. During this study effort I prepared a review of three beamed power concepts - pellet-stream-pushed, microwave-beam-pushed, and laser-beam-pushed systems - entitled, "Beamed Power Propulsion to the Stars." The paper was presented to the AAAS Symposium on Interstellar Communication and Travel at the AAAS Annual Meeting held from 25-30 May 1986 in Philadelphia, Pennsylvania. That paper is contained in Appendix A.

Because of the recent Space Defense Initiative (SDI) emphasis on high power lasers and large adaptive optical systems for directed energy weapons, laser powered beamed propulsion systems have become more feasible. A Laser Propulsion Workshop was held from 7-18 July 1986 at Lawrence Livermore National Laboratory in Livermore, California to investigate the feasibility of using some of the high power laser systems under development at LLNL for the SDI program as sources for testing laser propulsion concepts. The decision of the workshop was to concentrate on laser thermal propulsion from ground to low earth orbit. In this system, the vehicle carries its own propellant. The laser supplies the energy source to heat the propellant (water) to temperatures higher than could be reached using any chemical reaction. The accelerations are quite high (many times that of earth gravity) and the vehicle attains orbit before it goes out of sight of the ground-based laser-optical system.

As a contribution to the workshop, I carried out a study of the feasibility of using highly reflecting multilayer thin film structures driven by photon pressure from a laser beam. Very high terminal velocities (>100 km/s) of small (28 cm diameter), lightweight (0.3 g), ten-layer dielectric-film laser sails were predicted for a first generation laser system with a power level of 100 MW and a transmitter optical diameter of 10 m. The results of that study are presented in Appendix B.

OTHER PROPULSION CONCEPTS

In addition to the major effort on antiproton annihilation propulsion and the minor effort on beamed power propulsion, a number of other advanced propulsion concepts were investigated during the contract. Those studies carried far enough to be presented in papers or reports were investigations of the concepts of metallic hydrogen as a high energy rocket fuel, tether space transportation systems, and unconventional applications of solar sails. The latter two systems are discussed in a paper, "Exotic Propulsion in the 21st Century," AAS-86-409, presented at the 33rd Annual Meeting of the American Astronautical Society held in Boulder, Colorado from 26-29 October 1986.

RENEWING RESEARCH ON METALLIC HYDROGEN

In a prior study[7] carried out in 1983 on alternate propulsion energy sources, page 7-7 summarized the conclusions of a task to look at the feasibility of using metallic hydrogen for advanced propulsion. Metallic hydrogen is a postulated high energy propellant that releases its energy when the atomic metal is converted into gas molecules. The estimated specific impulse is 1700 s and the specific density is 1.15. It has been estimated[8] that pressures of 1.9 to 5.6 Mbar [megabars or million atmospheres] or equivalently 0.19 to 0.56 TPa [terapascals] would be needed to produce metallic hydrogen. There are some theoretical speculations that once metallic hydrogen is produced, it will be metastable and will remain in the metallic form when the pressure is released, while other theoretical estimates cast doubt on any metastable state.

At the time the previous study was completed in September 1983, the highest continuous pressure that had been obtained in the laboratory was 0.5 Mbar or 0.05 TPa. Thus, the recommendation of the previous study was that research on metallic hydrogen should "wait for the development of new high pressure machines that can produce steady megabar pressures."

In a recent issue of Science magazine, two reports indicate that perhaps the time has come to reevaluate the desirability of carrying out research on the formation of metallic hydrogen. In the first paper,[9] scientists at the Geophysical Laboratory, Carnegie Institution of Washington, have assembled a diamond anvil press that attained static pressures of 0.21 to 0.55 TPa (2.1 to 5.5 Mbars). These are an order of magnitude higher than had been achieved before and are the theoretically predicted pressure levels where metallic hydrogen should be formed.[8] If these pressures can be attained with molecular hydrogen in the sample chamber, then either metallic hydrogen will be formed or the theory will have been proved wrong. Either result will be of great scientific importance.

In the second paper,[10] scientists from Sumitomo Electric Industries in Japan, manufacturers of carat-sized single-crystal synthetic diamonds, demonstrated that their synthetic diamonds can be used as a pressure generator. Although their first attempt was terminated at a pressure of 68 GPa (0.68 Mbar) by the failure of one of the diamond anvils, their results suggest that synthetic diamond can be effectively used for pressure generation. There are a number of advantages to synthetic diamonds. First, their cost is extremely low. Six half-carat diamonds cost only $130. Second, they can be grown to large sizes in a repeatable fashion, although long bars and plates are easier than thicker lumps. Third, the synthetic diamonds can be made with controlled impurity levels, especially nitrogen, and it is known that substitutional nitrogen improves the strength of diamond. Thus, as the synthetic diamond growth process matures, it should be possible to make large, inexpensive, relatively high volume, very high pressure presses. As a result, carrying out the research and scaling up the process does not look formidable.

I therefore recommend that the Air Force look once again at carrying out in-house and sponsored research on metallic hydrogen. This would first involve the construction and use of high pressure diamond anvil presses to demonstrate the feasiblity of making metallic hydrogen. Then, if this research is successful, further fundamental research should be carried out on the properties of the metallic hydrogen as a function of temperature, pressure, time, applied magnetic field, nuclear and atomic spin state, purity, and type of chamber wall material. If this research is successful, then engineering studies should be started to determine the feasibility and cost of scaling up the research results to achieve production quantities of metallic hydrogen for testing as a rocket fuel.

TETHER SPACE TRANSPORTATION SYSTEMS

The concept of a stairway to heaven is a constant theme throughout mythology. In the Bible, Jacob dreamed that there was a ladder set up on the Earth, and the top of it reached to heaven, and the angels of God were ascending and descending on it. From the Far East came tales of magicians who could toss the end of a rope into the air, where it would stay, hanging from seemingly nothing. Then there is the ancient children's story of "Jack and the Beanstalk." It turns out that it may be possible to make these fairy tales come true.

Out at the very special distance of 36,000 km from the surface of the Earth (about six Earth radii), there now exist dozens of satellites in geostationary orbit. Suppose some friendly giant in one of those satellites were to let down a long cable – 36,000 km long. If the cable were strong enough to hold its own weight, then it would reach down to the surface of the Earth. It would be a Skyhook, a magic beanstalk in reverse. Given adequate supplies stashed along the way, a light-weight spacesuit, and enough time, Jack would be able to climb into space instead of having to use a rocket.

One of the first persons to think of the Skyhook concept was the Soviet engineer and popular science writer Yuri Artsutanov.[11] He unfortunately published the idea as a popular article in the

Sunday supplement section of Komsomolskaya Pravda (Young Communist Pravda) in 1960, where it was ignored by the West and subsequently reinvented a number of times. The final versions of a Skyhook system have two cables, one 36,000 km long going down to the surface of the Earth, and another 110,000 km long going outward to a ballast weight in order to keep the center of mass of the system at geostationary altitude. Theoretically, by putting a sufficient taper in the cable, it can be made of anything. In practice, there is no material presently available strong enough and light enough to make an Earth-going cable with an acceptable taper ratio.

A breakthrough in the production of long fibers of single crystal graphite or diamond might change the picture significantly. For example, actual measurements of tiny graphite whiskers show a tensile strength of 2.1×10^6 N/cm^2 or 3×10^6 lb/in.^{2}. With that strength, a 1 cm^2 cable of crystalline graphite could lift almost a 1000 km length of itself in the gravity field of the Earth. With a taper of 10:1, a graphite cable could be built to go all the way out to geostationary orbit, and beyond. The starter cable, which must be assembled in space and lowered down to the Earth, would have a mass of about 900 tonnes, have a diameter of about 1 mm at the Earth's surface, and be able to lift only 2 tonnes. This would suffice for a boot-strap operation that would allow more cable to be hoisted up from the ground.

If the Skyhook design used a number of cables arranged in a hollow structure, then electrified tracks could be built inside the structure. As each car climbed the skyhook from the Earth's surface into geostationary orbit, it would consume an appreciable amount of electrical energy. The cost of the electricity, $2/kg hauled into orbit, would be much less than the cost of using rockets, which is presently $5000/kg. Cars continuing beyond the geostationary point would be pulled along the cable by the ever-increasing centrifugal force. The cable cars would have to brake to keep from flying out too fast. If the braking were done by an elec ic motor, the braking energy could be turned into electricity and used to raise the next cable car up from the ground. On reaching the ballast mass, the cable car would be 150,000 km from the center of the Earth and moving with a tangential velocity of 11 km/s. If the cable car were to let go of the cable at just the right time, the car (now turned spacecraft) would be able to coast to Saturn on a minimum energy orbit or travel rapidly to all the other planets nearer than Saturn.

There is another version of the Skyhook that I call the Rotavator. It uses a cable that is much shorter than the geostationary orbit Skyhook. The Rotavator rotates as it orbits about the Earth, the ends of the cable touching down near the surface. This concept was also the brainchild of Yuri Artsutanov,[11] who published it as a popular article in the magazine Znanije-Sila (Knowledge-is-Force). The magazine illustrator's title drawing for the article shows a huge wheel rolling over the surface of a small Earth - an apt illustration of the concept since the rotating cable acts like a pair of spokes rotating inside an invisible wheel. It was Moravec, however, who published the first technical paper[12] on the concept.

The Moravec design for a Rotavator uses a 4000-km-long cable. This is one-third the diameter of the Earth, but only one-ninth the length of a 36,000 km geostationary Skyhook. The taper for a derated graphite cable would be about 10:1. To be able to lift a 100 tonne cargo into space it would have to mass about 5400 tonnes. The central portion of the cable would be put into an orbit that is 2000 km high with a period of 120 min. The cable would be set to spinning at one revolution every 40 min. Six times each orbit, once every 20 min, one of the ends of the cable would touch down into the upper regions of the Earth's atmosphere. Because of the large dimensions of the bodies involved, the ends of the cable would seem to come down into the upper atmosphere nearly vertically, with almost no horizontal motion. At touchdown the end of the cable would approach and leave the Earth with an acceleration of 1.4 Earth gravities. Counting the one gee field of the Earth itself, there would be a total acceleration at liftoff of only 2.4 gees, less than that at a Shuttle launch. Since even a stiff cable would have some stretch to it, there would be almost a full minute available for transferring cargo and passengers. After riding on the Rotavator for 20 min, you would be at the peak of the trajectory and traveling at 13 km/s. A payload released with this velocity could arrive at the orbit of Mars in 72 days and reach Venus in 41 days.

A Lunar Rotavator could be made with presently available materials, like the superfiber Kevlar made by DuPont. A 3700 tonne Kevlar Rotavator around the moon would be able to lift and deposit 100 tonnes every 20 min. Rotavators could also be put on all the smaller planets and moons. Similar spinning cables in solar orbits between the planets[13] could act as transfer points or "velocity banks" to cut the travel time between the planets in the solar system. As long as more mass is dropped inward down the gravity well of the Sun than is going out, no energy source would be needed to operate this interplanetary space transportation system once it was set into motion.

It won't be long before the first tethers will be flying in space as a Shuttle experiment.[14] NASA and the Piano Spaziale Nazionale of the Consiglio Nazionale Delle Ricerche (PNS/CNR) of Italy issued a joint Announcement of Opportunity OSSA-1-84 in 15 April 1984 for a Tethered Satellite System. A NASA built tether will be used to "troll" an Italian scientific satellite 100 km down from normal Space Shuttle altitude into the upper reaches of the atmosphere at 150 km. The Italian satellite mass is 500 kg and is spherical in shape with a tail to keep its aerodynamic instrument pointing in the forward direction. This half-tonne satellite will be supported by a very thin metallic or synthetic line 1 to 2 mm in diameter and 100 km or longer in length. Although the satellite mass is 500 kg, the tension expected in the cable is only 200 N (40 lb).

Once the NASA engineers have flown one or more of these systems without incident, then some of the more risky tether experiments can be attempted. A payload can be sent upwards many hundreds of kilometers from the Shuttle on a tether.[15,16] If the payload is released from the end of the tether, it will fly up to a higher elliptical orbit. The peak of this orbit could be high enough to catch onto a tether hanging down from a space station in geostationary orbit. Longer tethers could even launch a payload into an Earth-escape trajectory.

There is a serious problem with single strand tethers - cutting of the tether by meteorites or space debris.[17] Multistrand, cross-linked, fail-safe tether designs are needed. If this design problem can be solved, then as stronger high tensile strength materials become available, we may see this exotic propulsion system leap from the pages of the fairy tale books and send us bounding through the solar system on seven-league boots.

UNCONVENTIONAL MISSIONS USING SOLAR SAILS

The concept of solar sailing appears to have been first conceived by Russian space enthusiasts Tsander and Tsiolkovski back in the early 1920s. The most complete review[18] of the state of the art in solar sailing was carried out by a group at JPL back in 1976. Unfortunately, not much has been done since then.

A solar sail works by photon pressure from sunlight (the amount of pressure from the solar wind is negligible in comparison to the photon pressure). When light reflects from the surface of a body, the momentum of the light is reversed in direction. As a result, the body experiences a force proportional to the power in the light divided by the speed of light,

$$F = 2P/(c = ma)$$,

Where the factor 2 assumes normal incidence for the light on the reflective surface. Since the solar power flux at 1 AU is 1.4 kW/m^2, the solar force per unit area is about 9 N/km^2. The solar sail can be steered by tilting the sail to vary the direction of the resulting force vector. If the sail is in an orbit around the Sun, it can move outward by directing the force vector so that the sail speeds up, flying outward from the Sun. By tilting the sail so that it slows down, the sail will fall inward to the Sun. Since the maximum force is achieved when the sail operates near the Sun, most solar sail trajectories for interplanetary missions tend to first go inward to do their plane changes before heading out toward their target.

The 1976 JPL study[18] was a design for a solar sail to carry out a Halley rendezvous mission (as distinct from the high speed flyby missions that were actually carried out). The vehicle structure used masts and rigging to deploy a square sail 800 m (1/2 mile) on a side. The sail was made of 1-μm-thick aluminum-coated Kapton, weighing 1.2 g/m^2. The total flight vehicle mass was 3150 kg, with a payload bus of 861 kg. The optimum mission design would take 200 days to go inward to the Sun, where the sail would "crank" its orbit around the Sun for 225 days until it was going in a retrograde orbit matched with the retrograde orbit of Halley's Comet, then the sail would arc out in a long 506-day elliptical trajectory until it caught up and made the rendezvous with the incoming comet. The sail would be dropped, and the payload bus would stay with Halley through its entire trajectory around the Sun (and hopefully be revived 75 years later).

A 1 g/m^2 sail was a low risk project in 1976. Today we could do much better. One approach would be to replace the mast and spars with a rotating structure that would use ballast weights to maintain a wire support structure in tension. The 1976 JPL Heliogyro design[18] is one example; the 1979 Drexler high performance solar sail design[19] is another. It consists of a hexagonal structural mesh of wires held in tension by rotation. Each triangular section of a meter or so on a side would hold an unbacked ultrathin film of aluminum. For a 10-km-diameter sail with an area of $8x10^7$ m^2, the nonfilm structural mass is estimated as 0.03 g/m^2, while a thin film 30-nm-thick would mass 0.08 g/m^2, for a total areal density of 0.11 g/m^2. Such a solar sail would accelerate at almost 0.01 gees.

You can't make the reflective sail much thinner without its becoming transparent. But it still might be possible to decrease the mass per area without losing too much in reflectivity. As any radar engineer knows, you do not have to make a radar dish out of solid metal. You can make it out of chicken wire if the holes in the chicken wire are much smaller than a wavelength of the microwaves being used. Thus, it might be possible to make solar sails significantly lighter than present theoretical limits if we poke holes in the sail, as long as the holes are submicrometer in size so they are smaller than a wavelength of visible light. Techniques exist in the laboratory to make a thin perforated sail. Focused ion beams have already demonstrated the capability to make holes smaller than 0.1 μm, well below solar light wavelengths. Crossed holographic gratings have already been developed in photosensitive resists and used to make arrays of square posts with 0.2 to 0.5 μm spacing. The use of a positive rather than a negative resist would produce a square grating with similar-sized square holes. Such a thin, perforated sail could be produced using a plastic backing so that it could be handled and deployed. The plastic would be the type that would disintegrate in a short time under solar ultraviolet, leaving the perforated film. Once these high performance sails become a reality, they can be considered for exotic trajectories that are impossible with any other form of propulsion.

One of the potential applications of an ultrathin perforated solar sail is using light pressure from the Sun to levitate the orbit of a geostationary satellite up out of the equatorial plane.[20] At present, the only geostationary orbits are those along the equator at 35,800 km altitude (42,200 km from the center of the Earth). Although geostationary spacecraft can be seen at the Arctic and Antarctic Circles (depending on the local horizon topography), they cannot be used by ground stations near the poles.

If a spacecraft were supplied with a lightweight sail, it could use the sunlight to supply a constant force in the poleward direction. This would levitate the orbit out of the equatorial plane and the spacecraft would orbit about a point determined by the relative magnitude of the Earth gravity forces and the solar light pressure forces. The amount of displacement north or south of the equatorial plane is limited to a few hundred kilometers for unfurlable Kapton sails, and a few thousand kilometers for very thin solid-aluminum-film sails. By perforating the sail, however, we can improve the displacement distance significantly. Figure 4 shows a geostationary orbit that is levitated by the constant solar pressure 13,000 km northward from the equatorial plane, about twice the radius of the Earth.[20]

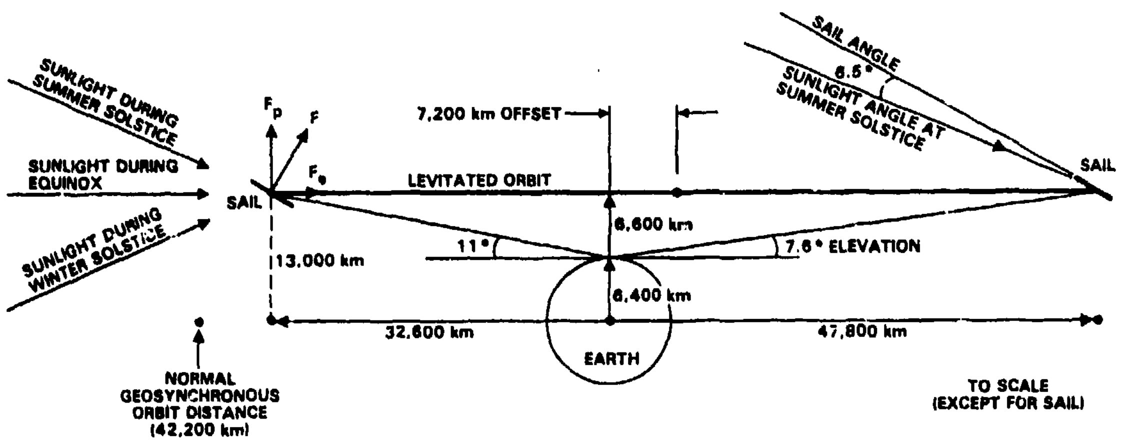

Figure 4. Polar levitated geostationary orbit.

The levitated orbit is noticeably displaced in the direction opposite to the Sun. (This effect was noticed on the Echo balloon satellite.) By varying the sail angle with the seasons, the levitated orbit can be kept synchronous with the Earth's rotation. The time of year chosen for Figure 4 is at summer solstice, where the Sun angle is the worst for providing northward thrust. In this worst case example, the position of the satellite is not truly geostationary. As seen from the north pole, it moves ±1.7° about its nominal elevation angle of 9.3°. The development of perforated solar sails and their use to create levitated orbits would not only relieve the pressure on the limited number of positions along the equatorial geostationary orbit, but would for the first time provide a true geostationary communications capability to the militarily important polar regions of the Earth.

Since the solar sail never runs out of fuel, it can be used to carry out exotic missions that are not conceivable using rocket propulsion. For example, a solar sail can hover in space, completely ignoring the usual constraints of orbital mechanics. One example is a shadow sitter that stays permanently in the shadow cone of a planet.[21] As shown in Figure 5, the shadow cone of the Earth extends out to 217 Earth radii. An Eclipsat with a sail made in the shape of a ring could then be placed to sit on the shadow cone, with its payload hanging in shadow. From this vantage point, the payload would see the Sun in a constant perfect total eclipse. From here scientific instruments could continuously monitor the solar corona for solar storms of importance not only to solar physicists but also to communication systems and space travelers. Since the gravity field of the Earth at 217 Earth radii is only 20 microgees, even a sail with a 1976 technology areal density of 1 g/m^2 could levitate a hefty scientific payload.

Since the source of the propulsion for solar sails is the Sun, they naturally work better closer to the source. In addition, the gravity field of the Sun varies as $1/R^2$ and the

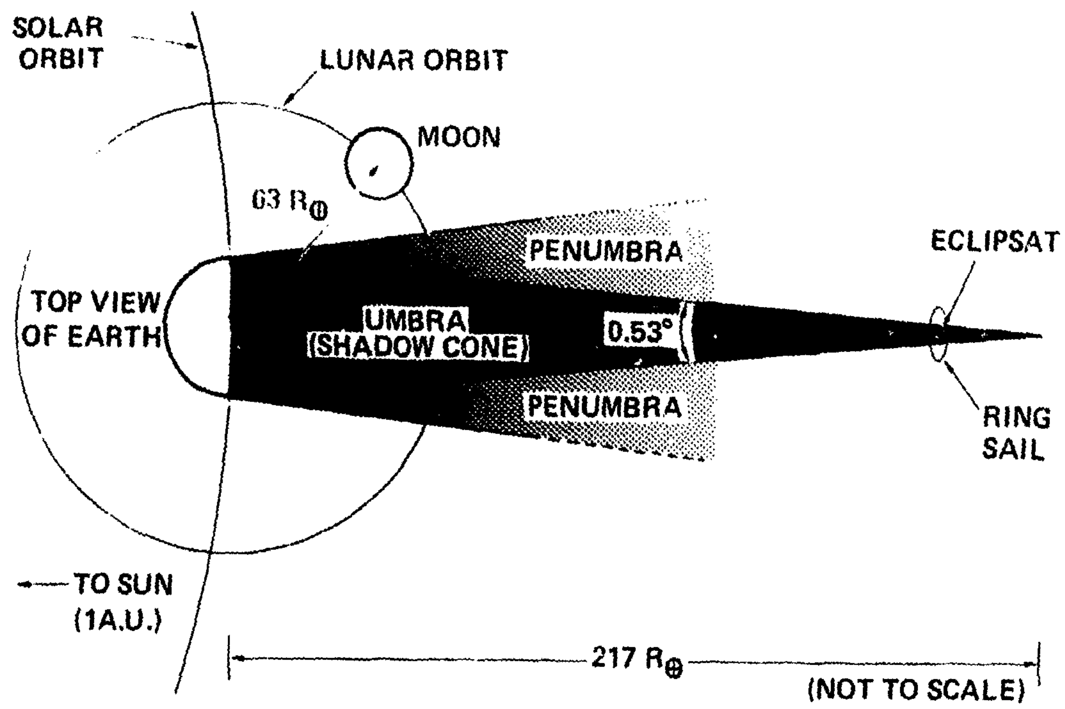

Figure 5. __Eclipsat__.

solar flux varies as $1/R^2$. Thus, once we get away from the gravity field of the planets, the performance of solar sails in the gravity field of the Sun is independent of distance. For a sail to be able to hover in the sunlight from the Sun, its mass-to-area ratio must be less than a certain value. This is determined by the balance between gravitational attraction and light pressure repulsion,

$$F = GMm/R^2 = 2P/c = 2SA/c \quad ,$$

where M is the mass of the Sun, m is the mass of the sail, and the total light power P is given by the solar flux S times the area A of the sail. For the distance of the Earth from the Sun of $R = 1\ AU = 1.5\times10^{11}$ m, the solar flux $S = 1400\ W/m^2$. With these numbers we can calculate the mass per unit area of sail and payload needed to just levitate the sail in the gravity field of the Sun:

$$m/A = 1.6 \text{ g/m}^2 \quad .$$

So it doesn't take a high performance sail to operate around the Sun.

One exotic mission for solar sails around the Sun would be to set up a set of scientific Sunwatchers to continuously monitor the changes in the solar surface. As is shown in Figure 6, we could place a number of high temperature sails in hovering orbits around the Sun. One could be placed over each pole to constantly monitor what is going on in the polar regions.[19] Others could be placed in solar synchronous orbits with a period matching that of the solar rotation at the latitude of interest. Note that because of the constant propulsive thrust capability of the solar sails, the resultant force vector can be used to cancel out a portion of the solar gravity pull, making the effective net attraction any value that you want, independent of the orbital radius. Thus, the orbital period can be decoupled from the orbital radius, and a 25-day solar synchronous orbit can have any altitude from the solar surface that is convenient.

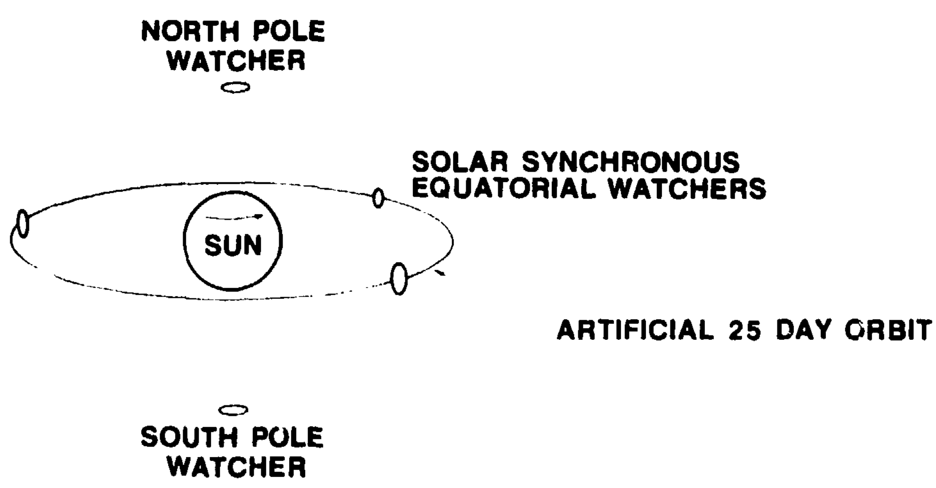

Figure 6. Sunwatcher sail system.

(Unfortunately this trick won't work for communication satellites around the Earth. The Sun is off to one side of the Earth and not at the center of the Earth.)

These are only a few of the exotic missions that can be performed with the only rocket ship that never runs out of fuel and lasts almost forever. Obtaining most of the more interesting missions, however, requires the development of high performance sails - probably perforated thin films. What is needed are good measurements of the performance of real films as a function of film thickness, hole size, and ratio of hole area to total area. We also need engineering studies of how these films might be fabricated, deployed, and supported during operation.

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APPENDIX A

BEAMED POWER PROPULSION TO THE STARS

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BEAMED POWER PROPULSION TO THE STARS

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BEAMED POWER PROPULSION TO THE STARS

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ABSTRACT

Although it is possible to use fusion or antimatter rockets for slow travel to the nearer stars, it may be that rockets are not the best vehicles for interstellar travel. Rockets consist of payload, structure, propellant, energy source, engine, and thruster. There is a whole class of spacecraft that do not have to carry any energy source or propellant or even an engine, and consist only of payload, structure, and thruster. These spacecraft work by beamed power propulsion. Many examples of beamed power propulsion systems have been published. Three will be discussed here. One is the pellet-pushed probe where small pellets are accelerated in the solar system and guided to an interstellar probe where they are intercepted and transfer momentum to the spacecraft. Then there is the maser pushed mesh probe. The basic structure is a wire mesh sail with microcircuits at each intersection. The mesh sail is pushed at high acceleration by a microwave beam. The high acceleration allows the sail to reach a coast velocity near that of light while still close to the transmitting lens. Upon arrival at the target star, the transmitter floods the star system with microwave energy. Using the wires as microwave antennas, the microcircuits collect energy to power their optical detectors and logic circuits to form images of the planets in the system. The picture information is then beamed back to earth. A third beamed power system is the laser pushed lightsail, where large sails of light-reflecting material are pushed to the stars by the photon pressure from a large laser array in orbit around the sun. The lightsail would reach relativistic velocity in a few years. Upon approaching the target system, a portion of the sail is detached from the center of the lightsail and turned to face the large ring sail that remains. The laser light from the solar system reflects from the ring sail which acts as a retro-directive mirror. The reflected light decelerates the smaller rendezvous sail and brings it to a halt in the target system. After the crew explores the system for a few years, a return sail is separated out from the center of the rendezvous sail. The laser light from the solar system hits the ring-shaped remainder of the rendezvous sail and is reflected back on the return sail, sending it back to the solar system. As the return sail approaches the solar system, it is brought to a halt by a final burst of laser power.

INTERSTELLAR TRANSPORT

It is difficult to go to the stars. They are far away, and the speed of light limits us to a slow crawl along the starlanes. Decades and centuries will pass before the stay-at-homes learn what the explorers have found. The energies required to launch a manned interstellar transport are enormous, for the mass to be accelerated is large and the cruise speed must be high. Yet these energies can be obtained once we move our technology out into space where the constantly flowing sunlight is a never-ending source of energy--over a kilowatt per square meter, a gigawatt per square kilometer. There are many ideas in the literature on methods for achieving interstellar transport [See bibliographies by Mallove, Forward, Paprotny and Lehmann, 1980; Paprotny and Lehmann, 1983; Paprotny, Lehmann, and Prytz, 1984 and 1985]. In time, one of these dreams will become a real starship.

It is not easy to comprehend the distances involved in interstellar travel. Of the billions of people living today on this globe, many have never travelled more than 40 kilometers from their place of birth. Of these billions, a few dozen have traveled to the Moon, which at almost 400,000 kilometers distance is ten thousand times 40 kilometers away. Soon, one of our interplanetary space probes will be passing the orbit of Pluto, ten thousand times further out at 4,000,000,000 kilometers. However, the nearest star at 4.3 light years is ten thousand times further than that.

To carry out even a one-way probe mission to the nearest star in the lifetime of the humans that launched the probe will require a minimum velocity of 0.1 c (10% of the speed of light). At that speed it will take the probe 43 years to get there and 4.3 years for the information to get back to us. The nearest star is called Proxima Centauri, part of a three star system called Alpha Centauri. One of the stars is similar to our sun. Further away are stars that are our best candidates for finding an earth-like planet. These are Epsilon Eridani at 10.8 lightyears and Tau Ceti at 11.8 lightyears. To reach these stars in a reasonable time will require probe velocities of 0.3 c. At this speed it will take nearly 40 years to get there, plus another 11-12 years for the information to return to earth. Yet, although we need to exceed 0.1 c to get to <u>any</u> star in a reasonable time, if we can attain a cruise velocity of 0.3 c, then there are 17 star systems with 25 visible stars and hundreds of planets within 12 lightyears [Forward, 1976]. This many stars and planets within reach at 0.3 c should keep us busy exploring while our engineers are working on faster starship designs. Although it is possible to use fusion or antimatter rockets for slow travel to the nearer stars, it may be that rockets are not the best way to go to the stars.

ROCKETLESS ROCKETRY

You don't have to use the rocket principle to build a starship. If we examine the components of a generic rocket, we find that it consists of payload, structure, propellant, energy source, an engine to put the energy in the propellant, and a thruster to expel the propellant to provide thrust. In most rockets the propellant and energy source are combined together into the chemical "fuel". Because a standard rocket has to carry its fuel along with it, its performance is significantly limited. For mission where the final vehicle velocity V is much greater than the exhaust velocity v, the amount of fuel needed rises exponentially as the ratio V/v.

It is possible to conceive of space vehicle designs that do not use the rocket principle and thereby avoid the exponential mass growth implicit in the design of a standard rocket. These are excellent candidates for starships. The Bussard interstellar ramjet [Bussard, 1960] is one example. The interstellar ramjet carries no fuel because it uses a scoop to collect the hydrogen atoms that are known to exist in "empty" space. The hydrogen atoms are used as fuel in a fusion engine, where the fusion energy is released and the energy fed back in some manner into the reaction products (usually helium atoms) which provide the thrust for the vehicle. Unfortunately, at this time, no one knows how to build either the proton fusion engine or the scoop (which must be very large in diameter as well as very low in mass).

BEAMED POWER PROPULSION

There is a whole class of spacecraft that do not have to carry along any energy source or propellant or even an engine, and consist only of payload, structure, and thruster. These spacecraft work by beamed power propulsion. In a beamed power propulsion system, the heavy parts of a rocket (propellant, energy source, and engine) are all kept in the solar system. Here, around the sun, there are unlimited amounts of propellant readily available, and the energy source (usually the abundant sunlight) and the engine can be maintained and even upgraded as the mission proceeds. Many examples of such beamed power propulsion systems that have been published in the literature, three will be discussed here. All of these versions can be built with "reasonable" extrapolations of present day technology. The examples are pellet-stream-pushed, microwave-beam-pushed, and laser-beam-pushed vehicles.

Pellet-Pushed Probes.

In the pellet-pushed-probe concept [Singer, 1980], small pellets are accelerated in the solar system and accurately guided to an interstellar probe where they are intercepted and transfer momentum to the spacecraft. By using pellets, the fundamental physical limitation of the spread of an electromagnetic beam with increasing distance can be overcome by using a particle beam rather than a photon beam for the momentum transfer. The pellets would be launched by a very long linear electromagnetic mass driver. The accelerator would be located in the Solar System and supplied by an energy source using nuclear or solar power. The pellet stream would be very carefully aimed immediately after launch and perhaps recollimated occasionally during flight. The pellets would be intercepted by the interstellar probe and reflected back in the opposite direction, the process resulting in an increase in momentum of the probe.

The absolute pointing accuracy of the mass launcher is not a serious limitation. The probe detects the incoming pellet stream and adjusts its position to stay in the stream. A series of course-correction stations could be located downrange from the launcher along the pellet stream. Each station, for example, would be three times farther downrange and would produce one-third as much velocity adjustment. The coarser adjustments could be made electromagnetically or electrostatically, and the finest adjustments could be made remotely by light pressure from a laser or by interaction with a plasma gun or neutral atom stream.

One method for accomplishing the interception of the high speed pellets at the vehicle is to vaporize them into a plasma with a pulse of photons or particles and then reflect the resultant plasma from a magnetic field in a manner somewhat analogous to the expulsion of plasma from a magnetic "nozzle" in a pulsed fusion rocket system [Hyde, Wood, and Nuckolls, 1972]. The size of the magnetic reflector should be at least as large as the radius of curvature of an incoming proton ion, which is 3 meters for an incoming pellet velocity of 0.1 c and a 10 tesla magnetic field. Extensions of the pellet stream concept include changing the pellet composition and velocity so that the pellets are fusion fuel that is captured at a low relative velocity, then used in a fusion engine for acceleration and deceleration. Deceleration at the target star system could also be accomplished by rebounding the pellets from an expendable unmanned lead ship to decelerate the manned vessel at the target system. Of course, once the "interstellar highway" has been traversed, then a pellet-stream launcher can be constructed at the other end for relatively easy two-way travel.

Starwisp: A Maser-Pushed Mesh Probe.

Starwisp is a light-weight, high-speed interstellar flyby probe pushed by beamed microwaves [Forward, 1985]. The basic structure is a wire mesh sail with microcircuits at each intersection. The mesh sail is pushed at high acceleration using a microwave beam formed by a large segmented ring transmitter lens made of alternating sparse metal mesh rings and empty rings [see Figure 1]. Such a configuration of rings will act as a crude, but effective, lens for a microwave beam.

The microwaves in the beam have a wavelength that is much larger than the openings in the wire mesh of the Starwisp starship, so the very lightweight perforated wire mesh looks like a solid sheet of metal to the microwave beam. When the microwave beam strikes the wire mesh, the beam is reflected back in the opposite direction. In turn, the microwave energy gives a push to the wire mesh sail. The amount of push is not large, but if the sail is light and the power in the microwave beam is high, the resultant acceleration of the starship can reach many times that of Earth gravity. The high acceleration of the starship by the microwave beam allows Starwisp to reach a coast velocity near that of light while the starship still close to the transmitting lens in the solar system.

Prior to the arrival of Starwisp at the target star, the microwave transmitter back in the solar system is turned on again and floods the target star system with microwave energy. Using the wires in the mesh as microwave antennas, the microcircuits on Starwisp collect enough energy to power their optical detectors and logic circuits to form images of the planets in the system. The direction of the incoming microwaves is sensed at each point of the mesh and that information is used by the microcircuits to transform the mesh wires into a microwave antenna that beams a signal back to Earth containing the picture information.

A minimal Starwisp would be a 1 kilometer mesh sail weighing 16 grams and carrying 4 grams of microcircuits. (The whole spacecraft weighs less than an ounce--you could fold it up and send it through the mail for the cost of first class postage.) This 20 gram starship would be accelerated at 115 gravities by a 10 gigawatt microwave beam, reaching 1/5th the speed of light in a few days. Upon arrival at Alpha Centauri 21 years later, Starwisp would collect enough microwave power to return real-time, high resolution color television pictures during its fly-through of the system.

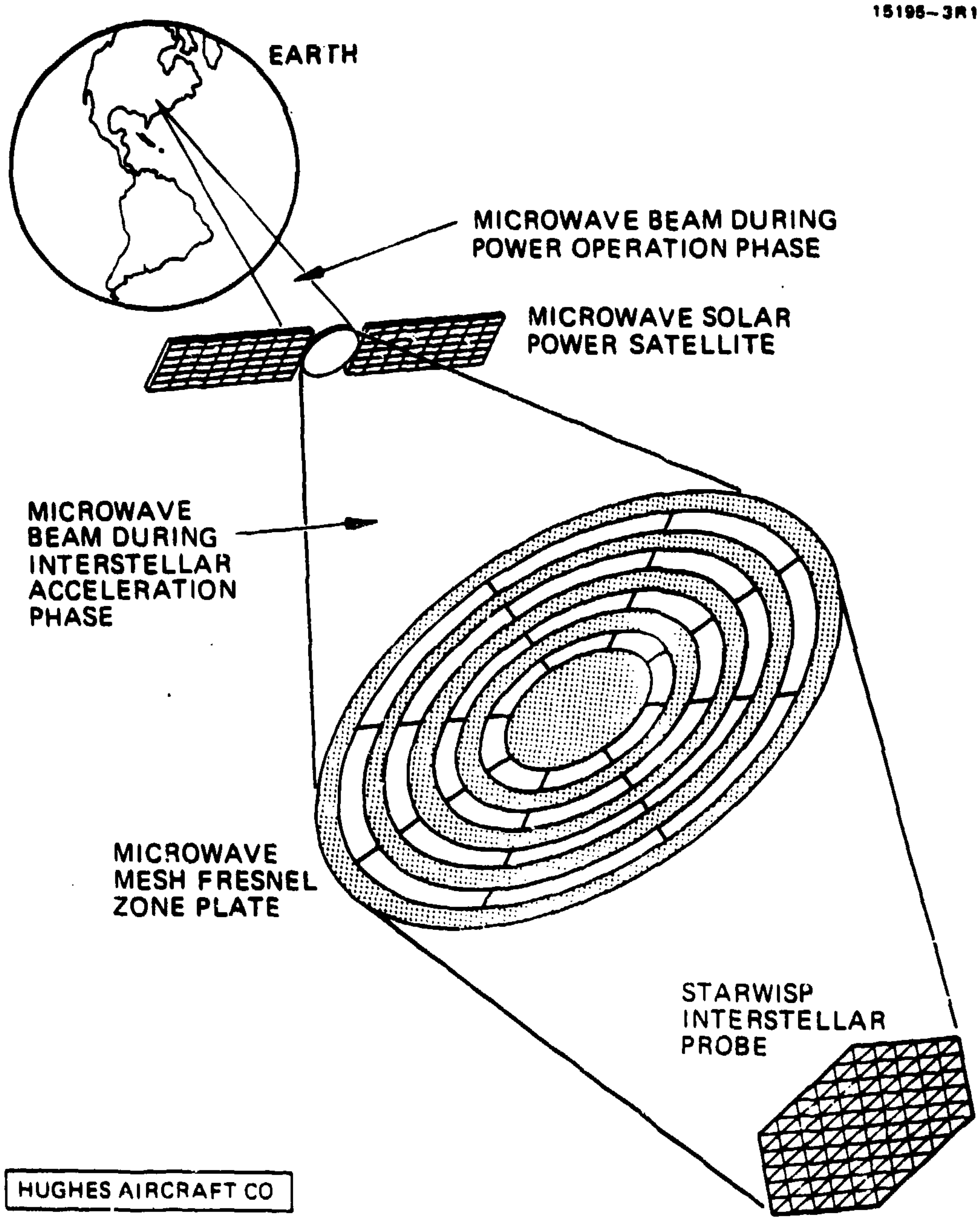

Figure A-1. **Starwisp: A Maser-Pushed Interstellar Probe.**

Because of its very small mass, the beamed power level needed to drive a minimal Starwisp is about that planned for the microwave power output of a solar power satellite. Thus, if power satellites are constructed in the next few decades, they could be used to launch a squadron of Starwisp probes to the nearer stars during their "checkout" phase. Once the Starwisp probes have found interesting planets, then we can visit those planets using another form of beamed power propulsion, called laser sail propulsion. Although microwave beams can only be used to "push" a robotic spacecraft away from the solar system, if we go to laser wavelengths, then it is possible to design a beamed power propulsion system that can use laser beams from the solar system to send a starship to the nearer stars, and then bring the starship and its crew back home.

Laser-Pushed Lightsails.

One of the best methods for traveling to the stars would use large sails of light-reflecting material pushed by the photon pressure from a large laser array in orbit around the sun [Forward, 1984]. With this technique we can build a spacecraft that can not only carry a large human crew at reasonable speeds to the nearest stars, but can also stop to allow the crew to explore, then return the crew back to earth again within a human lifetime.

In laser sail propulsion, light from a powerful laser is bounced off a large reflective sail surrounding the payload. The lightsail is made of thin aluminum film stretched over a supporting structure that in turn is attached to the payload. The light pressure from the laser light pushes the sail and payload, providing the needed thrust. The laser sail starship is about as far from a rocket as is possible. The starship consists of nothing but the payload and the lightweight sail, which is both structure and thruster. The engine of our starship is the laser, the energy source is the Sun, and the propellant is the laser light itself.

The sails that the laser craft would use would be advanced versions of the Sun-pushed lightsails that have been designed by the NASA Jet Propulsion Laboratory for comet missions and fast trips to the asteroid belt. The lasers would be advanced versions of the high power laser arrays presently being studied by the Space Defense Initiative Organization of the Department of Defense. The important thing to realize is that no scientific breakthroughs are needed to build this starship. The basic physical principles of the lasers, the transmitter lens, and the sail are known. All that is required to make the laser sail starship a reality is a lot of engineering (and a lot of money).

The lasers would be in space and energized by sunlight collected by large reflectors. For pushing an interstellar starship, the lasers would probably work better if they were in orbit around Mercury. There is more sunlight there and the gravity attraction of Mercury would keep them from being "blown" away by the reaction from their light beams. They would use the abundant sunlight at Mercury's orbit to produce coherent laser light, which would then be combined into a single coherent laser beam and sent out to a transmitter lens floating between Saturn and Uranus.

The transmitter lens would be a segmented ring lens 1000 kilometers in diameter with a mass of about 560,000 tons. It would consist of wide rings of extremely thin plastic film alternating with empty rings. The width of the rings would be tuned to the laser frequency. The transmitter lens would not be in orbit, but would either be freely falling (very slowly at that distance from the Sun), or "levitated" in place by rockets or by the momentum push from a portion of the laser light passing through it. A lens this size can send a beam of laser light over 44 lightyears before the beam starts to spread. This insures that no light is lost to spreading of the light beam for the entire duration of the mission.

We will want a starship design that can carry out roundtrip missions to stars as distant as Tau Ceti and Epsilon Eridani within a human lifetime. The lightsail would be built in three sections [see Figure 2]. There is an inner payload sail that is 100 kilometers in diameter. Surrounding that is an inner ring-shaped sail that is 320 kilometers in diameter with a 100 kilometer hole. Surrounding that is an outer ring-shaped sail that is 1000 kilometers in diameter with a 320 kilometer diameter hole. The total structure would mass 80,000 tons, including 3,000 tons of payload consisting of the crew and their habitat, supplies, and exploration vehicles.

The entire lightsail structure would be accelerated at 30% of Earth gravity by 43,000 terrawatts of laser power. (Since the Earth only produces about 1 terrawatt of electrical power, we would certainly want to use the free solar power in space instead of trying to get our power from Earth.) At this acceleration, the lightsail would reach a velocity of half the speed of light in 1.6 years. The expedition would reach Epsilon Eridani in 20 years Earth time and 17 years crew time, and it will be time to stop. At 0.4 lightyears from the target star, the outer ring sail would be separated from the two inner portions. The inner portions would be allowed to lag behind while they are being turned to face the large outer ring sail. The laser light coming from the solar system would reflect from the outer ring sail acting as a retro-directive mirror. The reflected light decelerates the two inner portions and brings them to a halt at Epsilon Eridani.

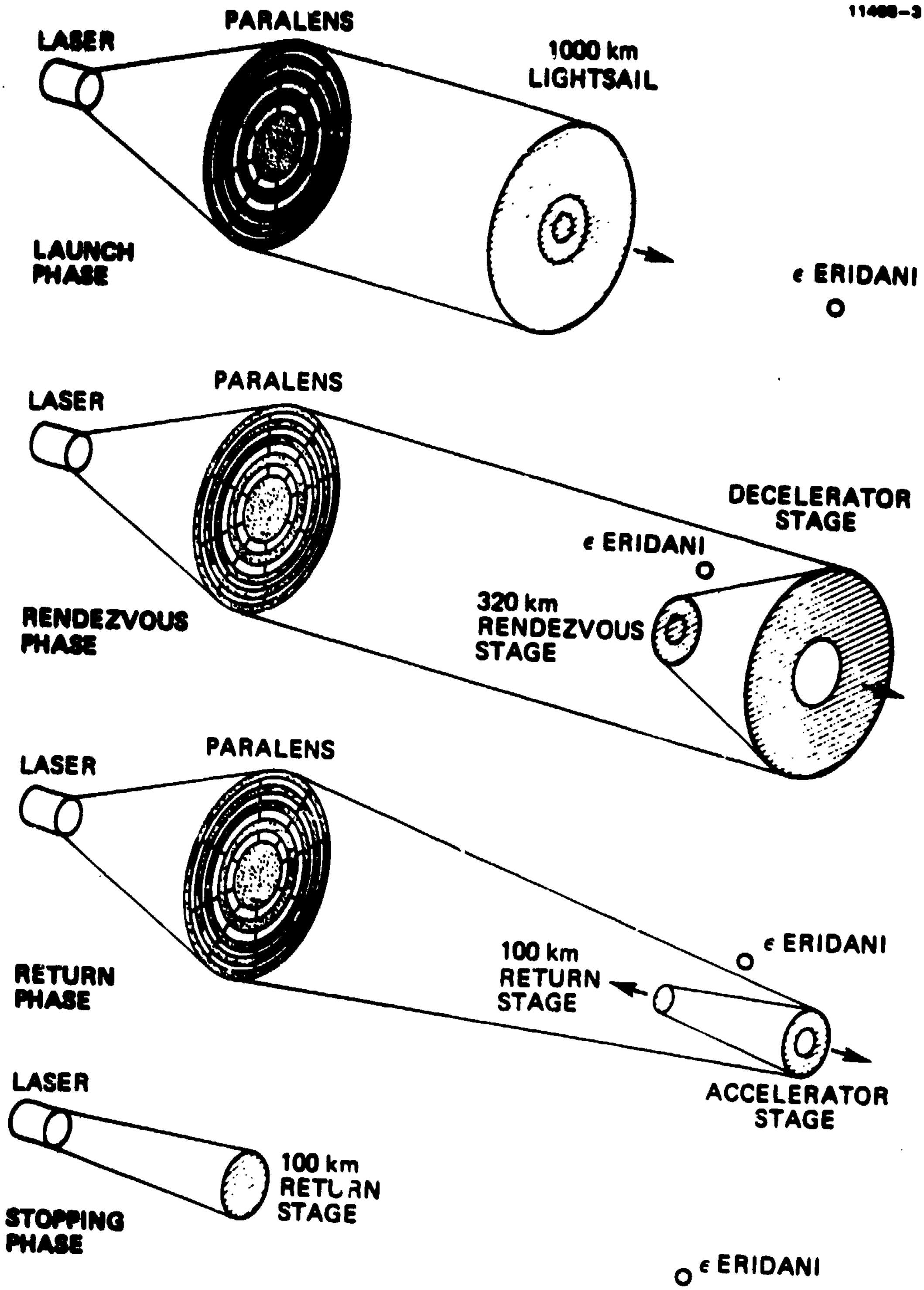

Figure A-2. Roundtrip Interstellar Travel Using Laser-Pushed Lightsails.

After the crew explores the system for a few years (using their lightsail as a solar sail), it will be time to bring them back. To do this, the smaller ring sail is detached from the payload sail and they turn to face each other. Provided someone back in the solar system remembered to turn on the laser beam 12 years earlier, the laser beam from the solar system hits the ring-shaped sail and is reflected back on the payload sail. The laser light then accelerates the payload sail back toward the solar system. As the payload sail approaches the solar system 20 Earth-years later, it is brought to a halt by a final burst of laser power. The members of the crew have been away 51 years (including 5 years of exploring), have aged 46 years, and are ready to retire and write their memoirs.

CONCLUSION

It is difficult to go to the stars, but it is not impossible. There are not one, but many different technologies, all under intensive development for other purposes, that, if suitably modified and redirected, can give the human race a flight system that will reach the nearest stars. All it really takes is the desire and the commitment to a few decades of hard space engineering work and our first interstellar probe could be heading to the stars within our lifetimes.

ACKNOWLEDGEMENTS

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APPENDIX B

LASER WEAPON TARGET PRACTICE WITH GEE-WHIZ TARGETS

LASER WEAPON TARGET PRACTICE WITH GEE-WHIZ TARGETS

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LASER WEAPON TARGET PRACTICE WITH GEE-WHIZ TARGETS

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ABSTRACT

I propose that small, lightweight, highly reflecting targets be used to test ground based laser weapon systems. The targets would be deployed outside the atmosphere by a sounding rocket. The photon pressure from the laser beam would be used to drive the targets outward at high accelerations to reach extremely high terminal velocities--the fastest objects in the solar system. The targets would test the system pointing, tracking, and focusing subsystems in a non-destructive manner that would blunt criticism of the tests. Since the light reflected by the targets could be seen from the ground, the tests would allow for public viewing from anywhere in the continental United States.

INTRODUCTION

I will assume that at some point in the development of a high power laser weapon system that it would be desirable to demonstrate the long distance pointing, tracking, and focusing capabilities of the laser weapon system on an exo-atmospheric object at distances of many earth radii. There are lots of obvious targets that could be imagined, ranging from old left-over orbiting satellites to sophisticated simulations of real targets. The one proposed here is different. It would not only test many of the features of a laser weapon system, but would do so in a fashion that was non-destructive (thus blunting criticism of the test). It would also provide for public participation to partially repay the U.S. taxpayers for the money they have invested in the development of the system.

The target would be a sheet of highly reflective material that would be deployed outside the atmosphere by a vertical sounding rocket. After deployment, the slowly falling target would be picked up by the laser beam from the ground based laser weapons. The target would be accelerated by light pressure until it reached the maximum terminal velocity possible. If the test is carried out at night, the reflected light from the rapidly rising target should be visible over a good part of the northern hemisphere (the sail being designed to spread the reflected beam so there would be no eye hazard). If everything works right, the lightsail would become "the fastest object in the solar system" (about 100 km/s). Within a year it would outdistance our other interstellar probes, the Pioneer and Voyager spacecraft, and be on its way out of the solar system. More advanced and larger lasers and transmitting apertures could push advanced versions of these lightsail targets to a few percent of the speed of light.

LASER WEAPON PARAMETERS

We will assume that the laser has an average power level P, wavelength λ, and transmitting aperture D. It will be on the surface of the earth. The actual laser weapon parameters are classified, but we can assume the following: Wavelength λ varies from 0.1 to 10 μm with a nominal value of 1 μm. If the laser light is to be visible to the public the wavelength should be chosen to be 0.5 μm. Power P varies from 0.1 to 10 GW with a nominal value of 1 GW. Diameter of transmitter aperture D varies from 1 to 100 m with a nominal value of 10 m.

LIGHTSAIL TARGET PARAMETERS

The lightsail target will be assumed circular. If it is a beamrider sail, it may have a small hole in the middle, which we shall ignore in this first cut analysis. It will have a diameter d, an average areal density β, a reflectivity on the laser side of η, an emissivity on the other side of ϵ, and an absorptance α. In prior analyses [Forward 1984], I assumed an extremely thin aluminum sail that actually allowed a good fraction of the incident laser light to pass through it. For these proposed lightsail targets, we will assume a much thicker multilayer film designed with high reflectivity on the front surface (η=0.999+) and a highly emissive coating on the back (ϵ=0.95+). Thus, any laser light transmitted through the front surface will essentially be absorbed by the internal structure or the emissive coating on the back. Thus the absorptance α is related to the reflectance η by $\alpha=1-\eta$.

Depending upon the melting or aggolomeration properties of the high reflection coatings and absorbing films, the lightsail target will have a safe operating temperature T. The power on the lightsail is going to be large and there is a real danger of blowing it into blobs of molten glass and metal. The irradiance times will be many tens of seconds, which implies for these thin film structures that we have thermal equilibrium between the laser power leaking into the lightsail and infrared radiation radiating away. The thermally limited acceleration for a lightsail was derived in a previous paper [Forward 1984] as:

$$a = \frac{4\sigma\epsilon\eta T^4}{c\alpha\beta}$$

where $\sigma=5.67\times10^{-8}$ W/m^{2}K^4 is the Stefan-Boltzmann constant. I have also assumed that the emitted infrared radiation from the emissive coating on the back is not affected by the multilayer reflective coating on the front, since the multilayer film is tuned to a narrow wavelength band.

For a sail of diameter d, the mass is:

$$m = \frac{\pi}{4} \beta d^2$$

The power needed to push this lightsail using photon pressure is:

$$P = \frac{mca}{2\eta} = \frac{\pi c \beta d^2 a}{8\eta} = \frac{\pi \sigma \epsilon d^2 T^4}{2\alpha}$$

The constant acceleration phase stops when the diameter of the laser beam becomes larger than the diameter of the lightsail. The distance s over which the lightsail acceleration stays constant is:

$$s = \frac{Dd}{2.44\lambda}$$

The lightsail will reach this distance in a time:

$$t = (2s/a)^{1/2}$$

with a velocity of:

$$v = (2as)^{1/2} = at$$

We will now arrange the various parameters to maximize the terminal velocity of the lightsail for a given laser power, wavelength, and transmitter diameter. By simple algebraic manipulation, it can be shown that:

$$v^4 = 6.8 \frac{\sigma \epsilon P \ \eta^2 D^2 \ T^4}{\alpha \ \lambda^2 \beta^2 c^2}$$

The sail diameter that corresponds to this maximum terminal velocity can be shown to be:

$$d^2 = \frac{2\alpha P}{\pi \sigma \epsilon T^4}$$

REFLECTIVITY OF MULTILAYER THIN FILMS

The reflectivity of multilayer thin films can be extremely high if the films are constructed of pairs of quarter-wave thick layers of low absorptance dielectrics. People working on films for coating laser reflectors have achieved 0.9999+ for a particular wavelength in the visible. The multilayer thin film reflectors are made of a quarter wave thick film of high index of refraction n_H followed by a quarter wave thick film of low index of refraction n_L. The thickness of a layer with a given index of refraction n_H is given by:

$$t_H = \lambda/4n_H$$

The areal mass of the layer is then just:

$$\beta_H = t_H\rho_H = \lambda\rho_H/4n_H$$

Where ρ_H is the density of the material in the layer with the high index of refraction.

The total areal mass of one double layer of high and low index of refraction material is then:

$$\beta_1 = \beta_H + \beta_L$$

and for N layers

$$\beta_N = \frac{N\lambda}{4}\left[\frac{\rho_H}{n_H} + \frac{\rho_L}{n_L}\right]$$

The formula for the reflectivity is given in handbooks [Driscoll 1978] as:

$$\eta = \frac{[1-(n_L/n_H)^{2N}]^2}{[1+(n_L/n_H)^{2N}]^2}$$

Where n_L is the lower index of refraction and n_H is the higher index of refraction and N is the number of pairs. The formula assumes that there is no substrate index of refraction and the outer layers see the index of refraction of air or vacuum. This may have to be modified if there is an emissive coating on the back, but I suspect it will have no effect on a highly reflective coating.

For a large number of dielectric reflector pairs, this formula reduces to:

$$1-\eta = 4(n_H/n_L)^{2N} \simeq \alpha$$

Thus, we see that after we have paid the price of the first few dielectric pair layers, that the reflectivity increases rapidly with the addition of a few more layers while the mass of those layers only rises linearly with the number of layers. In a typical film pair, two more layers (from 10 to 12 layers) causes a decrease in absorptance by a factor of ten (10^{-4} to 10^{-5}) but only increases the weight by 20%.

FIRST GENERATION MULTILAYER FILM TARGET

A standard dielectric film pair used for high reflectivity coatings at visible wavelengths consists of a layer of ZnS with n_H=2.35, ρ_H=3900 kg/m^3, quarter-wave thickness t_H=53 nm, and a melting point of 1823K, alternating with a layer of MgF_2 with n_L=1.38, ρ_L=3150 kg/m^3, quarter-wave thickness t_L=90 nm, and a melting point of 1534K. The areal density of a single reflecting pair is β_1=4.9x10^{-4} kg/m^2.

We can now look at the use of a multilayer lightsail target made out of a multilayer thin film of these two materials. We will assume that the lightsail is made only of the film, with no substrate, and the backside emissive surface mass is negligible. We will assume it is well made, however, and the emissivity of the backside is a good ϵ=0.99. For a lightsail target made out of a 10 pair stack, the reflectivity is four nines, η=0.9999, the absorptance is a maximum of $\alpha \simeq 1-\eta = 10^{-4}$ and the areal mass of the sail is only β=4.9x10^{-3} kg/m^2. With melting points of 1500K and above, we will also assume that we can run this lightsail target in the vacuum of space at T=1100K without severe damage for the few minutes it will be irradiated.

Since this will be a first generation test, we will assume modest values for the laser power of P=100 MW and transmitter diameter of D=10 m. We will assume a visible wavelength of λ=0.5 μm so the results of the tests can be observed on the ground. When all these values are substituted in the previously derived general equations we get the following:

At this power level, the lightsail target will be accelerated at 2300 m/s^2 or about 230 gees. It will reach a terminal velocity of 100 km/s after about 45 seconds at a distance of 2300 km. The optimum lightsail target to obtain this terminal velocity has a diameter of 28 cm (about a foot) and weighs 0.3 grams.

SECOND GENERATION DIAMOND PLY TARGET (A RELATIVISTIC TRAP SHOOT)

After the laser weapon has been upgraded to a power level of $P=10^9$ W and a transmitting aperture of D=100 m, then we can try trapshooting with near-relativistic targets. At these higher power densities we will need a much stronger, higher reflecting, and higher melting temperature target. I propose that the target consist of quarter-wave thick layers of diamond separated by a quarter-wave of vacuum (with submicrometer spacer posts to maintain the spacing between the diamond layers. Artificial diamond with controlled amounts of nitrogen to increase the strength are now commercially available in large plates. Diamond has an index of refraction $n_H=2.4173$, density $\rho=3510$ kg/m^3, quarter-wave thickness $t_H=51$ nm, areal density $\beta=1.81\times10^{-4}$ kg/m^2, and a graphite conversion temperature beginning at 1800 K. Eight layers of diamond alternating with vacuum is sufficient to give a reflectivity of $\eta=0.999997$ and an absorptance $\alpha\simeq1-\eta=3\times10^{-6}$.

If we assume that we can operate the diamond lightsail target at a temperature of T=1700 K, then the thermally limited acceleration is a remarkable 1.5×10^6 m/s^2 or about 150,000 gees. The velocity obtainable with these parameters is found to be $v=4.5\times10^6$ m/s or 1.5% of the speed of light. The diameter of the diamond lightsail target is d=6.4 cm and because there are a small number of layers and the alternating layers of vacuum have no mass, the total mass of the target is only 4.5 mg. The target will be accelerated over a distance of 5200 km, which is about one earth radius. It will reach that distance in 2.6 s.

VERIFICATION AND TESTING OF LIGHTSAIL TARGETS

Since the lightsail targets are very small and lightweight, they can be tested on the ground by using medium power lasers to levitate them in the 1 gee gravity field of the earth. For example, the diamond lightsail targets that are 6.4 cm in diameter and mass 4.5 mg can be levitated in a 1 gee field by only 7 kW of laser power. The multilayer thin film sail would require a lot more power to levitate, nearly 4 MW, but that sail could be adequately tested by levitating only a small portion of it to prove out the reflectivity. The high temperature thermal characteristics would be harder to verify.

CONCLUSIONS

Laser weapons can be tested in a dramatic and non-threatening fashion that would be visible to the public by using them to drive highly reflecting lightsail targets to high velocities. If such targets are desired, then some research needs to be done to verify the high reflectivities that are predicted theoretically. The lightsail targets can be tested at low laser power levels on the ground prior to use.

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APPENDIX C

EXOTIC PROPULSION IN THE 21ST CENTURY

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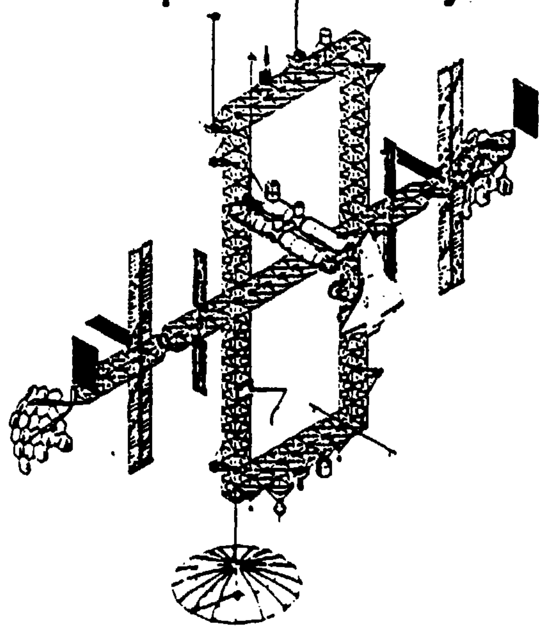

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EXOTIC PROPULSION IN THE 21ST CENTURY*

Robert L. Forward+

Chemical propulsion has taken us to the moon and planets. Solar and nuclear electric propulsion will shorten trip times, but we still won't have the rapid interplanetary travel of Buck Rogers in the 25th Century. Some truly exotic forms of propulsion will come into being in the 21st Century that may change all this. First is laser propulsion. High gee launch from earth to orbit of unmanned payloads up to 10 tonnes looks feasible and may even be cost effective. Second is tether propulsion. Rotating cables in space can be used to lift payloads from a planetary body and throw them through space at hyper-escape velocities. Third is antimatter propulsion, where microgram crystals of antihydrogen stored in electrostatic traps are injected into a reaction chamber where they annihilate with normal matter to produce high energy charged particles called pions. The pions transfer their energy to the reaction fluid to provide thrust. Fourth is lightsail propulsion. Reflective sails will use sunlight to obtain high specific impulse, low thrust propulsion for orbit raising, plane changes, and rendezvous missions to comets and asteroids. Perforated lightsails can place payloads in exotic trajectories unobtainable by normal orbital dynamics, such as geostationary orbits that are not on the geostationary arc. By combining laser propulsion with lightsail propulsion we can travel to the stars. A laser beam from the solar system not only can push a lightsail to the stars at substantial fractions of the speed of light, but also can be used with multistage sails to rendezvous at the target star and then bring the crew back to the solar system in a human lifetime.

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INTRODUCTION

Chemical propulsion has lifted us off the planet, taken us to the moon, and sent our robotic probes throughout the solar system. Advanced propulsion concepts such as solar and nuclear electric propulsion are under development to improve trip times and lower the mass ratios required for interplanetary missions, but they are still far from giving us the rapid interplanetary space travel exemplified by Buck Rogers in the 25th Century. As we look forward just 14 years to the beginning of the 21st Century, we see a need for new and exotic forms of space propulsion. This need has been recognized by NASA and DoD for many years and there have been a series of excellent studies[1-7] looking at the feasibility of a number of advanced propulsion ideas. Some of these have been ion thrusters, electric plasma thrusters, resistojets, arcjets, MPD thrusters, solar thermal jets, solar sustained plasma thrusters, laser thermal thrusters, tethers, solar sails, chemically bound excited states (metastable helium, spin polarized atomic hydrogen, metallic hydrogen, tetrahydrogen), nuclear thermal propulsion, nuclear electric propulsion, fusion propulsion, tethers, skyhooks, solar sails, enthalpy rockets, lasing the ionosphere, antimatter propulsion, extracting energy from the vacuum, elementary particle catalyzed fusion, field reaction propulsion, and beamed power propulsion. This paper will expand on five of the more exotic of these advanced propulsion concepts: laser thermal propulsion, tethers, antiproton annihilation propulsion, solar sails, and laser pushed lightsails.

LASER THERMAL PROPULSION

Laser thermal propulsion systems use energy beamed from a distant high power laser to heat a propellant. The expansion of the propellant provides thrust as in a chemical rocket. Laser thermal propulsion can produce high thrust at higher specific impulse than chemical rockets, generally 500 to 2000 seconds. Since the high power laser and its power supply do not have to be on the vehicle they can be optimized for maximum performance without undue consideration for weight or size.

Although beamed power laser propulsion using photon pressure on lightsails had been proposed by Forward[8] in 1962 shortly after the invention of the laser, the first serious proposal for laser thermal propulsion was made by Kantrowitz[9] in 1972, shortly after the advent of high power CO_2 lasers. Laser propulsion studies[10,11] supported by NASA, DARPA, and the Air Force have concentrated on orbital maneuvering missions requiring modest thrust levels and therefore modest laser power levels of a few megawatts. Until recently there did not appear to be much prospect of obtaining the gigawatt lasers needed to launch payloads from the surface of the earth.

Now, however, because of defense needs and the Space Defense Initiative, advances have been made in high power lasers, especially free electron lasers, as well as the pointing, tracking, and compensating optics needed to form and direct high power diffraction limited beams over distances of thousands of kilometers. These advances have led to serious proposals to use these lasers and optical systems to launch significant payloads from the earth's surface directly into orbit. A recent workshop on laser propulsion[12] was held at Lawrence Livermore Laboratory, future home of a high power free electron laser.

One recommendation of the workshop was that a program of research and development be started that would lead to the launch of a test payload into orbit as sketched in Figure 1. The system used would be a flat plate (nozzle-less) repetitively pulsed laser-supported detonation wave thruster. The pulsed detonation-wave thruster should achieve a specific impulse of 800 seconds and an energy efficiency (useful jet kinetic energy/laser energy) of 40%. With short laser pulse widths, the travel distance of the detonation wave is so short that there is no need for a nozzle or skirt. The thrust is generated efficiently using only the expansion of the heated working fluid against the flat base of the launch vehicle.

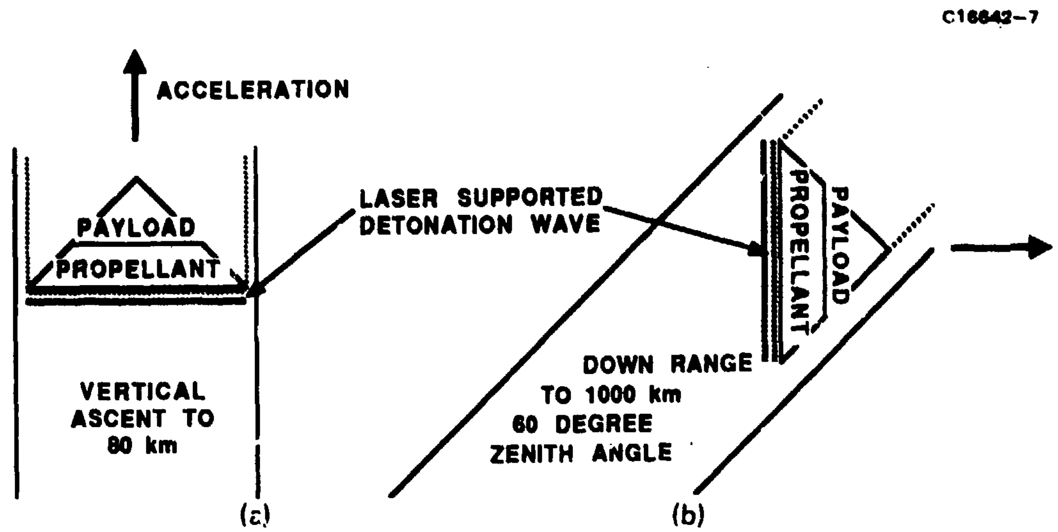

Figure C-1. Laser Thermal Propulsion from Ground to Orbit.

Since it is the expanding exhaust producing the thrust, the thrust vector is always normal to the vehicle base, independent of the angle of incidence of the laser. As is shown in Figure 1b, the flat-plate laser thermal rocket can accelerate at large angles to the laser beam. Vehicles could be steered from the ground by simply moving the laser beam off the center of the reaction plate. Thus, a very simple vehicle, consisting of only payload and a solid inert propellant, could carry payloads directly into low earth orbit at low cost. The broad conical shape of the payload section protects the sides of the vehicle from stray laser light, even at large offset angles.

Some preliminary studies indicate that for a thruster efficiency of 40%, a specific impulse of 800 seconds, and a drag coefficient of 0.5, a 100 MW laser can launch a 1 metric tonne vehicle into low earth orbit. With a mass ratio of 7.4, the final payload of 136 kg is delivered into orbit in 13 minutes, having been subjected to a peak acceleration of 5.6 gees. A 1 GW laser is projected to be able to launch up to 64,000 tonnes per year into low earth orbit at an electricity cost of about $18/kg. Capital and other costs would likely raise this to $100/kg.

The key research needed in the immediate future is the modelling and experimental measurement of the one-dimensional detonation wave behavior with selected propellants. We need to understand the process of detonation wave initiation and thrust generation with chemically and physically complex propellants, so that an efficient propellant can be designed, fabricated, and characterized. This work can be done with existing lasers, although some modifications to generate double pulses may be needed. A more detailed system study is also needed to investigate issues such as ground-based attitude sensing and control of the vehicle by variations in laser beam flux distribution and beam pointing.

Once an adequate understanding of the detonation wave physics and propellant chemistry is obtained, then engineering development of thrusters and vehicles could begin. This development would be paced to make use of large free electron lasers, such as PALADIN, ALEX (an infrared FEL), ALEX-prime (a 1 μm FEL with a beam director), as they become available. An installation such as ALEX-prime should be capable of launching test payloads to low Earth orbit in the early 1990s.

This work on advanced laser thermal propulsion is now moving into a more active R&D phase. As a result of the Laser Propulsion Workshop[12], the SDIO has decided to commence a program in laser propulsion in connection with its major program in ground-based lasers. The program will be under the sponsorship of the Directed Energy Office. The total laser propulsion budget for the 1987 fiscal year will be approximately $2 million. Proposals for laser propulsion research are being solicited from anyone with an interest in the field. The proposals will be reviewed by a Program Steering Committee, initially consisting of Freeman Dyson, Arthur Kantrowitz, Edward Teller, and Gregory Canavan, and chaired by SDIO's Col. Tom Meyer. The goal of the program is attaining an Earth-to-orbit launch capability paced by the availability of ground-based lasers. This new program will give researchers full access to the next generation of lasers which the SDI is creating and will make available many opportunities for sponsored research on all aspects of laser thermal propulsion.

TETHER TRANSPORTATION SYSTEMS

The concept of a stairway to heaven is a constant theme throughout mythology. In the Bible, Jacob dreamed that there was a ladder set up on the Earth, and the top of it reached to heaven, and the angels of God were ascending and descending on it. From the Far East came tales of magicians who could toss the end of a rope into the air, where it would stay there, hanging from seemingly nothing. Then there is the ancient children's story of "Jack and the Beanstalk". It turns out that it may be possible to make these fairy tales come true.

Out at the very special distance of 36,000 kilometers from the surface of the Earth (about six Earth radii), there now exist dozens of satellites in geostationary orbit. Suppose some friendly giant in one of those satellites were to let down a long cable--36,000 kilometers long. If the cable were strong enough to hold its own weight, then it would reach down to the surface of the Earth. It would be a Skyhook, a magic beanstalk in reverse. Given adequate supplies stashed along the way, a light-weight spacesuit, and enough time, Jack would be able to climb into space instead of having to use a rocket.

One of the first persons to think of the Skyhook concept was the Soviet engineer and popular science writer Yuri Artsutanov.[13] He unfortunately published the idea as a popular article in the Sunday supplement section of

Komsomolskaya Pravda (Young Communist Pravda) in 1960, where it was ignored by the west and subsequently reinvented a number of times. The final versions of a Skyhook system have two cables, one 36,000 km long going down to the surface of the Earth, and another 110,000 km long going outward to a ballast weight in order to keep the center of mass of the system at geostationary altitude. Theoretically, by putting a sufficient taper in the cable, it can be made of anything. In practice, there is no material presently available that is strong enough and light enough to make an Earth-going cable with an acceptable taper ratio.

A breakthough in the production of long fibers of single crystal graphite or diamond might change the picture significantly. For example, actual measurement of tiny graphite whiskers show a tensile strength of 2.1×10^6 N/cm^2 or 3×10^6 $lb/in.^2$. With that strength, a one square centimeter cable of crystalline graphite could lift almost a 1000 km length of itself in the gravity field of the Earth. With a taper of 10:1, a graphite cable could be built to go all the way out to geostationary orbit, and beyond. The starter cable that must be assembled in space and lowered down to the earth would have a mass of about 900 tonnes, have a diameter of about 1 mm at the Earth's surface and would be able to lift only 2 tonnes. This would suffice for a boot-strap operation which would allow more cable to be hoisted up from the ground. If the Skyhook design used a number of cables arranged in a hollow structure, then electrified tracks could be built inside the structure. As each car climbs the skyhook from the Earth's surface into geostationary orbit, it would consume an appreciable amount of electrical energy. The cost of the electricity, $2 per kilogram hauled into orbit, would be much less than the cost of using rockets, which is presently $5000/kg. Cars continuing beyond the geostationary point would be pulled along the cable by the ever-increasing centrifugal force. The cable cars would have to brake to keep from flying out too fast. If the braking were done by an electric motor, the braking energy could be turned into electricity and used to raise the next cable car up from the ground. On reaching the ballast mass, the cable car would be 150,000 km from the center of the Earth and moving with a tangential velocity of 11 km/s. If the cable car were to let go of the cable at just the right time, the car (now turned spacecraft) would be able to cost to Saturn on a minimum energy orbit or travel rapidly to all the other planets nearer than Saturn.

Mars is the best planet in the solar system for a Skyhook,[13] having both a shallow gravity well and a high rotation rate. Since the 24.5 hr rotation rate for Mars is nearly the same as that of Earth, while its gravity field is 38% that of Earth, a Mars Skyhook using graphite would have to mass only 42 times what it could lift. Mars also has a 21 km high mountain on the equator, Mons Pavonis, that can be used as an anchor point, and a small moon, Deimos, that is available at almost just the right orbit to act as the counterweight.

There is another version of the Skyhook that I call the Rotavator. It uses a cable that is much shorter than the geostationary orbit Skyhook. The Rotavator rotates as it orbits about the Earth, the ends of the cable touching down near the surface. This concept was also the brainchild of Yuri Artsutanov,[13] who published it as a popular article in the magazine Znanije-Sila (Knowledge-is-Force). The magazine illustrator's title drawing for the article shows a huge wheel rolling over the surface of a small earth--an apt illustration of the concept since the rotating cable acts like a pair of spokes rotating inside an invisible wheel. It was Moravec, however, who published the first technical paper[14] on the concept.

The Moravec design for a Rotavator uses a cable that is 4000 km long. This is one-third the diameter of the Earth, but only one-ninth the length of a 36,000 km geostationary Skyhook. The taper for a derated graphite cable would be about 10:1. To be able to lift a 100 tonne cargo into space it would have to mass about 5400 tonnes. The central portion of the cable would be put into an orbit that is 2000 km high with a period of 120 min. The cable would be set to spinning at one revolution every 40 min. Six times each orbit, once every 20 min, one of the ends of the cable would touch down into the upper regions of the Earth's atmosphere. Because of the large dimensions of the bodies involved, the ends of the cable would seem to come down into the upper atmosphere nearly vertically, with almost no horizontal motion. At touchdown the end of the cable would approach and leave the Earth with an acceleration of 1.4 Earth gravities. Counting the one gee field of the Earth itself, there will be a total acceleration at liftoff of only 2.4 gees, less than that at a Shuttle launch. Since even a stiff cable would have some stretch to it, there would be almost a full minute available for transferring cargo and passengers. After riding on the Rotavator for 20 min, you are at the peak of the trajectory and are traveling at 13 km/s. A payload released with this velocity could arrive at the orbit of Mars in 72 days and reach Venus in 41 days.

A Lunar Rotavator could be made with presently available materials, like the superfiber Kevlar made by DuPont. A 3700 tonne Kevlar Rotavator around the moon would be able to lift and deposit 100 tonnes every 20 min. Rotavators could also be put on all the smaller planets and moons. Similar spinning cables in solar orbits between the planets[15] could act as transfer points or "velocity banks" to cut the travel time between the planets in the solar system. As long as more mass is dropped inward down the gravity well of the Sun than is going out, no energy source would be needed to operate this interplanetary space transportation system once it was set into motion.

It won't be long before the first tethers will be flying in space as a Shuttle experiment.[16] NASA and the Piano Spaziale Nazionale of the Consiglio Nazionale Delle Ricerche (PNS/CNR) of Italy issued a joint Announcement of Opportunity OSSA-1-84 in 15 April 1984 for a Tethered Satellite System. A NASA built tether will be used to "troll" an Italian scientific satellite 100 km down from normal Space Shuttle altitude into the upper reaches of the atmosphere at 150 km. The Italian satellite masses 500 kg and is spherical in shape with a tail to keep its aerodynamic instrument pointing in the forward direction. This half-tonne satellite will be supported by a very thin metallic or synthetic line one to two millimeters in diameter and 100 km or longer in length. Although the satellite masses 500 kg, the tension expected in the cable is only 200 N (40 lb).

Once the NASA engineers have flown one or more of these systems without incident, then some of the more risky tether experiments can be attempted. A payload can be sent upwards many hundreds of kilometers from the Shuttle on a tether.[17,18] If the payload is released from the end of the tether, it will fly up to a higher elliptical orbit. The peak of this orbit could be high enough to catch onto a tether hanging down from a space station in geostationary orbit. Longer tethers could even launch a payload into an Earth escape trajectory.

Once we have a permanent manned base on Mars, it may be possible that tethers can be used to make an inexpensive Earth-Mars transportation system. Penzo[19] has shown that for the price of a launch into low Martian orbit, a payload can be sent all the way to Earth. As is seen in Figure 2, after the payload is lifted up by rocket out of the Martian atmosphere into low Martian orbit, it is sent upward from the launch vehicle on a 375 km tether. It is released at that point and has enough energy to fly out to 8000 km from

Mars, where it will rendesvous with a 1160 km downgoing tether from Phobos. Using electrical power supplied by a solar power station on Phobos, the payload is lifted up to Phobos at 9400 km from Mars, and sent out an outgoing 940 km tether. It releases from there and now has enough energy to rendesvous with a 2960 km tether hanging down from Deimos out at 23,500 km distance. It climbs that tether to Deimos, then continues on out the 6100 km outgoing tether from Deimos. Out here the payload has enough velocity to go into an escape orbit from Mars back to the Earth.

There is a serious problem with single strand tethers--cutting of the tether by meteorites or space debris.[28] Multistrand, cross-linked, fail-safe tether designs are needed. If this design problem can be solved, then as stronger high tensile strength materials become available, we may see this exotic propulsion system leap from the pages of the fairy tale books and send us bounding through the solar system on seven-league boots.

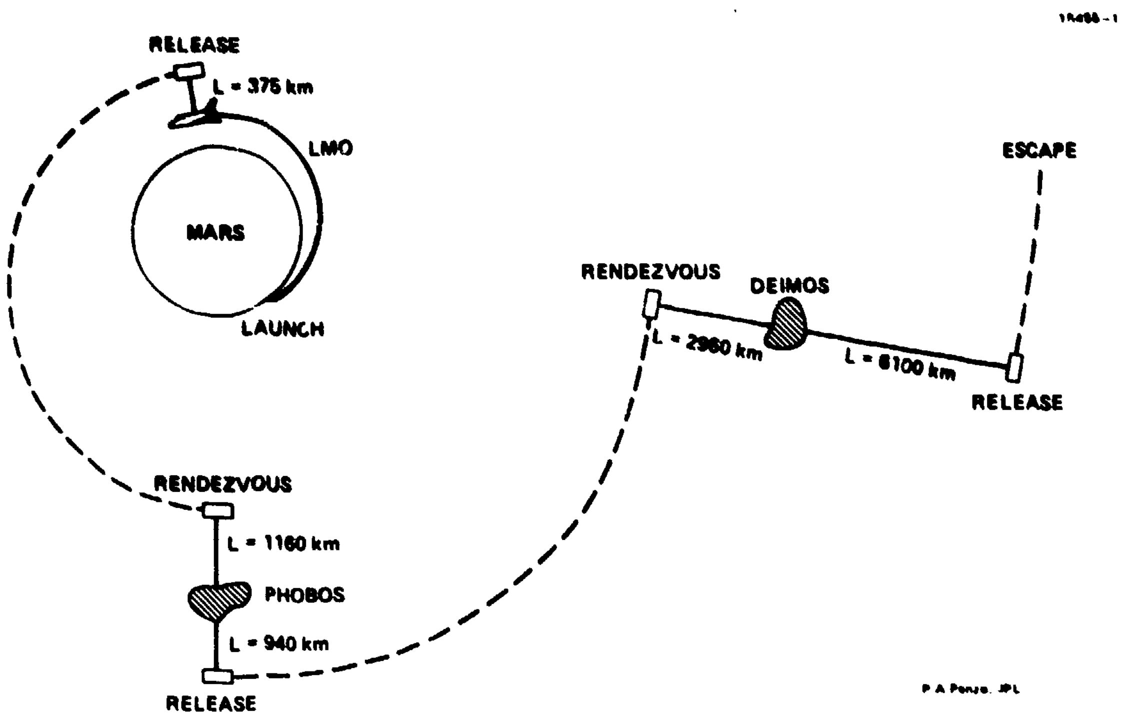

Figure C-2. Mars Tether Transportation System

ANTIPROTON ANNIHILATION PROPULSION

A major new exotic form of propulsion has just graduated from the never-never land of science fiction and has now become a serious topic for scientific and engineering investigation. In the past it was called antimatter propulsion, but to emphasize the difference between past fiction and present reality, I prefer to call it antiproton annihilation propulsion,[21] for the use of antiprotons as the form of the antimatter is crucial to the use of antimatter for propulsion.

For every particle known to exist, there is a mirror image twin particle that has its charge, spin, and quantum states reversed from that of normal particles. As shown in Figure 3, the stable particles that make up atoms--electrons, protons, and neutrons have mirror twins called positrons, antiprotons, and antineutrons. Conceptually, these could be combined to form antiatoms such as antihydrogen.

When a particle comes near its antiparticle, they attract each other and annihilate each other, totally converting all of their rest mass into energy. When positrons and electrons annihilate they produce gamma rays, which are difficult to convert to thrust, but when antiprotons annihilate with protons, the annihilation process does not produce gamma rays immediately; instead, the products of the annihilation are from 3 to 7 pions. On the average there are 3 charged pions and 2 neutral pions. The neutral pions have a very short lifetime and almost immediately convert into two high energy gamma rays. The charged pions have a normal half-life of 26 ns. Because they are moving at 94% of the speed of light, however, their lives are lengthened to 70 ns. Thus, they travel an average of 21 m before they decay. This lifetime and interaction length are easily long enough to collect the charged pions in a thrust chamber constructed of magnetic fields. As is shown in Figure 4, the energy in the pions can then either be used to heat a working fluid such as hydrogen to produce thrust, or the high speed pions themselves can be directed by a magnetic nozzle to produce 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.[21]

Since antimatter does not exist naturally, it must be made, one particle at a time. It is a synthetic fuel. It will

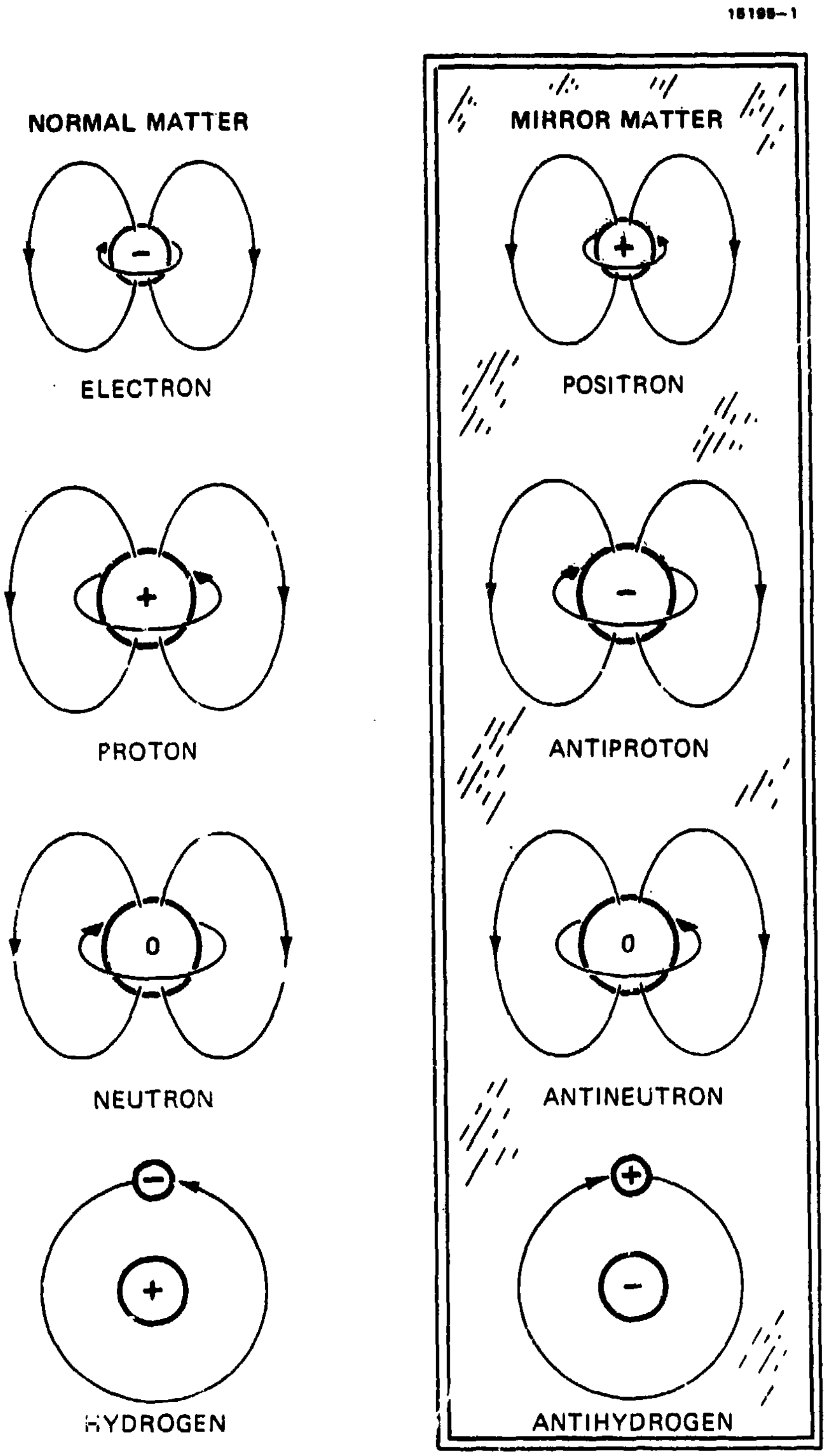

Figure C-3. Normal Matter and Mirror Matter

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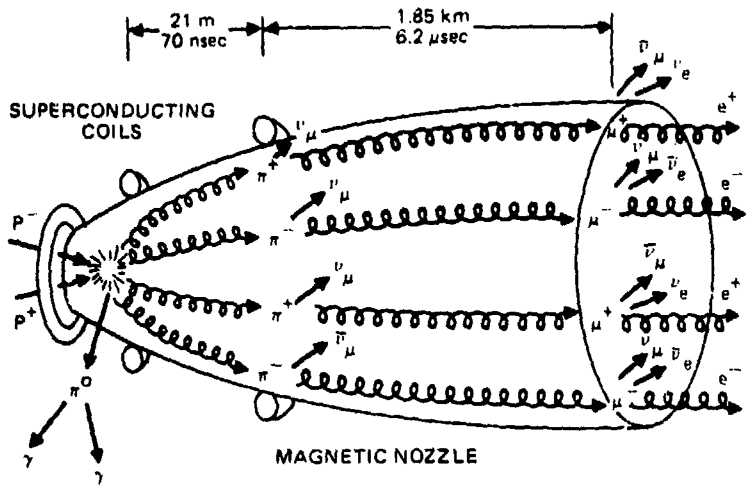

Figure C-4. Schematic of Antiproton Annihilation Propulsion.

always require much (~10^4 times) more energy to produce antimatter than can be extracted from the annihilation process. Its major advantage is that it is a highly concentrated form of energy storage. A tenth of a milligram, about the size of a single grain of salt, contains the energy of 2 tonnes of the best rocket fuel known, liquid oxygen/liquid hydrogen. Since any fuel in space presently costs 5 M$/tonne just to lift it into space, if we can make antimatter for significantly less than 100 M$/mg, then it might be a cost effective fuel for space propulsion.

A study which compared antihydrogen propulsion systems with chemical propulsion systems[22] found that antiproton propulsion could possibly be cost effective for space propulsion. More importantly, it was mission enabling, in that it would allow missions to be performed that are essentially impossible to perform with chemical fuels. The best example is a simple sortie mission from a space station to inspect or pick up a satellite orbiting in the opposite direction. This maneuver requires cancelling the initial orbital velocity and rebuilding it again in the opposite direction. Since orbital velocity about the earth is 7.7 km/s, the mission characteristic velocity (ΔV) is 15.5 km/s. If it is then desired to return to the orbiting base, the total ΔV is 31 km/s. To accomplish this mission using even LOX/hydrogen fuel would require a vehicle with a mass ratio of 500, which is impossible to build. The same mission can be accomplished using antiprotons with a mass ratio of 3:1 and 20 mg of antimatter per tonne of dry vehicle.

The recent in-depth study[21] of the feasibility of antiproton annihilation propulsion explored in great detail the many steps needed to make the concept feasible. It was determined that antiproton annihilation propulsion was physically feasible, in that there where no known "showstoppers" that would prevent it from being accomplished, but it was difficult and expensive. Whether it would be a cost effective method of propulsion was not clear and would depend upon the results of research and experiments to be carried out in the coming decades.

Antimatter in the form of antiprotons is being made today, albeit in small quantities. As is shown in Figure 5, 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 into a storage ring. These collecting rings have stored as many as 10^{12} antiprotons for days at a time. 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 amount of energy.

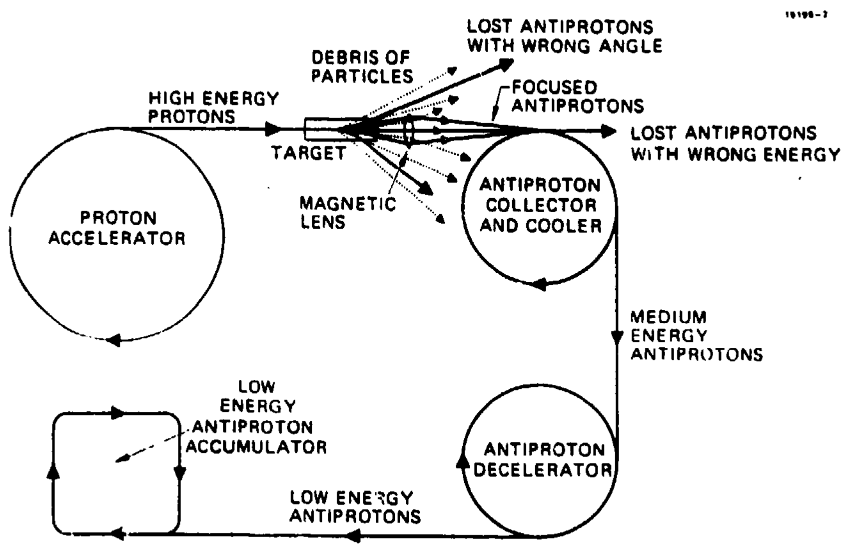

Figure C-5. Present Method of Making Antiprotons

In a recent experiment[23], a team of scientists took the low energy antiprotons in one of these rings, slowed them down to almost zero velocity, and captured a few hundred antiprotons in a small electromagnetic ion trap. Other experiments planned for late 1987 will attempt to capture many millions of antiprotons in a trap no bigger than a thermos bottle. The electromagnetic trap will be made portable so that the antiprotons can be transported to other laboratories for experiments. The funding for these trapping experiment groups comes from DoD, DOE, and NSF and will amount to many millions of dollars by 1988.

On order to use antiprotons as a propulsion fuel, it will be necessary to find a more compact method of storage than an ion trap, which are limited to relatively low ion densities. Another Air Force sponsored research program is looking into adding positrons to the antiprotons in the ion traps and slowly building up "cluster ions" of antihydrogen. These are large agglomerations of neutral antihydrogen atoms clustered around a single antiproton ion. The net negative electric charge of the cluster ion allows it to be kept in the ion trap, yet the mass of each ion can be increased until we have an ice crystal with enough charge that it can be electromagnetically levitated without touching the walls of the cryogenically cooled trap.

In use, the small microcrystals, each weighing about a microgram and having the energy content of 20 kg of LOX/hydrogen, would be extracted electromagnetically from the trap, directed by electric fields down a vacuum line with shutters to maintain the trap vacuum, then shot with a carefully selected velocity into the rocket chamber where the antiprotons will annihilate with the reaction fluid, heating it up to provide high thrust at high specific impulse. The annihilation cross-section increases dramatically at low relative velocity, so the annihilation process occurs mostly at the center of the chamber.

Designs of rocket engines to use antimatter are well underway at a number of engineering laboratories. One simple design[24] is based on the NERVA nuclear rocket, with the nuclear reactor replaced with a tungsten heat exchanger core. The reaction products (both gammas and pions) would be stopped in the tungsten and the energy used to heat hydrogen gas passing though the heat exchanger. This engine would use 13 μg/s of antiproton fuel to produce a specific impulse of 1100 s at a thrust level of 4.4×10^5 N (100,000 lb) for a power level of 2.7 GW. Such an engine could take 100 tonnes of payload to Mars and back in six months (only three months each way) with a mass ratio of 4. By comparison, a

LOX/hydrogen system would require a mass ratio of 18 and would take 12 months to get there and 9 months to get back.

Studies have also started on magnetic bottle reaction chambers[25] which have the potential of attaining higher specific impulse than engines limited by the thermal properties of matter. Analysis of plasma transport coefficients has identified two parameter regimes of practically lossless operation of a magnetic nozzle with a pure hydrogen plasma. The one of interest for an antimatter heated hydrogen plasma thruster is optically thick, with a density of 3×10^{19} ions/cm^3, a temperature of 2 eV (23,000 K), a magnetic field of 5 T, a throat dimension of 1 m, and a pressure of 1000 psi (67 atm).

Because antiproton propulsion promises a major advance in space propulsion capability, the recently completed Air Force Systems Command Project Forecast II study recommended that the Air Force start a new program in antimatter propulsion. As a direct result of the Project Forecast II recommendations, the Air Force Rocket Propulsion Laboratory at Edwards AFB in California has reorganized its advanced propulsion activities and formed a new project called ARIES (Applied Research In Energy Storage). The project has two major thrusts, chemically bound excited states and antimatter. About one-third of the budget is allocated to antimatter. The Air Force Office of Scientific Research has initiated a new program on antimatter research in the Physical and Geophysical Sciences Branch under Col. Hugo Weichel. The Program Manager for Antimatter is Maj. John Prince, who evaluates unsolicited proposals for research on antimatter sciences. In Europe, an Antimatter Research Team (ART) has been formed at Telespazio, SpA per le Comumicazioni Spàziali in Italy. Their research work[26] will cover antiproton and positron production and storage, and engine simulations, leading ultimately to technology demonstrations.

If the next decade of experimental research on cooling and trapping of antiprotons, the growth and storage of antihydrogen, and the design studies of antimatter rockets and antimatter powered missions shows promise, then engineering studies will commence on the design and ultimate fabrication of an antiproton factory capable of producing about a microgram a year (compared to the present nanogram per year). A microgram of antiprotons with an energy of 100 MJ could power a test stand run of a 1 MW feasibility demonstration rocket engine for 100 s. At that point a lot more would be known about the engineering feasibility, cost effectiveness, and desirability of antiproton annihilation propulsion. Then a decision could be made whether to proceed with the construction of an antiproton factory that could produce the hundreds of milligrams a year needed to run a space program. Such a factory could be designed to be self-powering, but would require a capital investment comparable to building a 10 GW power plant.

EXOTIC MISSIONS USING SOLAR SAILS

The concept of solar sailing appears to have been first conceived by Russian space enthusiasts Tsander and Tsiolkovski back in the early 1920s. The most complete review[27] of the state of the art in solar sailing was carried out by a group at JPL back in 1976. Unfortunately, not much has been done since then.

A solar sail works by photon pressure from sunlight (the amount of pressure from the solar wind is negligible in comparison to the photon pressure). When light reflects from the surface of a body, the momentum of the light is reversed in direction. As a result, the body experiences a force that proportional to the power in the light divided by the speed of light.

$$F=2P/c=ma$$

Where the factor two assumes normal incidence for the light on the reflective surface. Since the solar power flux at 1 AU is 1.4 kW/m^2, the solar force per unit area is about 9 N/km^2. The solar sail can be steered by tilting the sail to vary the direction of the resulting force vector. If the sail is in an orbit around the sun, it can move outward by directing the force vector so that the sail speeds up, flying outward from the sun. By tilting the sail so that it slows down, the sail will fall inward to the sun. Since the maximum force is achieved then the sail operates near the sun, most solar sail trajectories for interplanetary missions tend to first go inward to do their plane changes before heading out toward their target.

The 1976 JPL study[27] was a design for a solar sail to carry out a Halley rendezvous mission (as distinct from the high speed flyby missions that were actually carried out). The vehicle structure used masts and rigging to deploy a square sail 800 m (1/2 mile) on a side. The sail was made of 1 μm thick aluminum coated Kapton, weighing 1.2 g/m^2. The total flight vehicle mass was 3150 kg with a payload bus of 861 kg. The optimum mission design would take 200 days to go inward to the sun, where the sail would "crank" its orbit around the sun for 225 days until it was going in a retrograde orbit matched with the retrograde orbit of

Halley's Comet, then the sail would arc out in a long 506 day elliptical trajectory until it caught up and made the rendezvous with the incoming comet. The sail would be dropped, and the payload bus would stay with Halley through its entire trajectory around the sun (and hopefully be revived 75 years later).

A 1 g/m^2 sail was a low risk project in 1976. Today we could do much better. One approach would be to replace the mast and spars with a rotating structure that would use ballast weights to maintain a wire support structure in tension. The 1976 JPL Heliogyro design[27] is one example, the 1979 Drexler high performance solar sail design[28] is another. As is shown in Figure 6, it consists of a hexagonal structural mesh of wires held in tension by rotation. Each triangular section of a meter or so on a side would would hold an unbacked ultrathin film of aluminum. For a 10 km diameter sail with an area of $8x10^7$ m^2, the non-film structural mass is estimated as 0.03 g/m^2, while a thin film 30 nm thick would mass 0.08 g/m^2 for a total areal density of 0.11 g/m^2. Such a solar sail would accelerate at almost 0.01 gees.

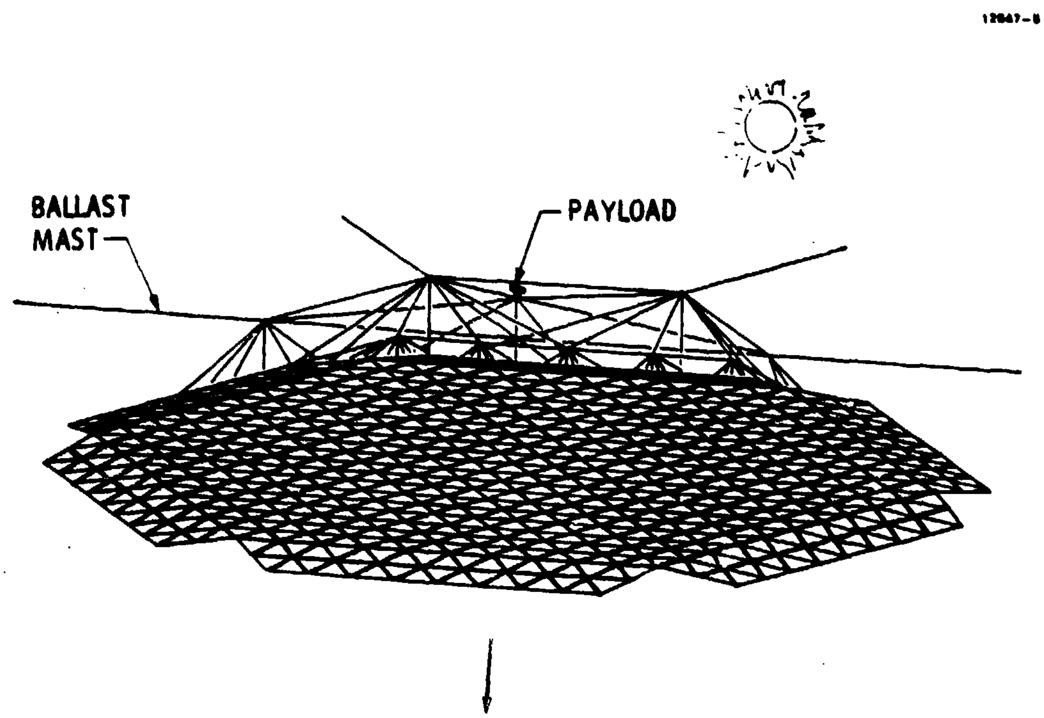

Figure C-6. High Performance Solar Sail Design

You can't make the reflective sail much thinner without it becoming transparent. But it still might be possible to decrease the mass per area without losing too much in reflectivity. As any radar engineer knows, you do not have to make a radar dish out of solid metal. You can make it out of chicken wire if the holes in the chicken wire are much smaller than a wavelength of the microwaves being used. Thus, it might be possible to make solar sails significantly lighter than present theoretical limits if we poke holes in the sail, as long as the holes are submicron in size so they are smaller than a wavelength of visible light. Techniques exist in the laboratory to make a thin perforated sail. Focused ion beams have already demonstrated the capability to make holes smaller than 0.1 μm, well below solar light wavelengths. Crossed holographic gratings have already been developed in photosensitive resists and used to make arrays of square posts with 0.2 to 0.5 μm spacing. The use of a positive rather an a negative resist would produce a square grating with similar sized square holes. Such a thin, perforated sail could be produced using a plastic backing so that it could be handled and deployed. The plastic would be the type that would disintegrate in a short time under solar ultraviolet, leaving the perforated film. Once these high performance sails become a reality, then they can be considered for exotic trajectories that are impossible with any other form of propulsion.

One of the potential applications of an ultrathin perforated solar sail is to use the light pressure from the sun to levitate the orbit of a geostationary satellite up out of the equatorial plane.[29] At the present time, the only geostationary orbits are those along the equator at 35,800 km altitude (42,200 km from the center of the earth). Although geostationary spacecraft can be seen at the Arctic and Antarctic Circles (depending upon the local horizon topography), they cannot be used by ground stations near the poles.

If a spacecraft were supplied with a lightweight sail, it could use the sunlight to supply a constant force in the poleward direction. This would levitate the orbit out of the equatorial plane and the spacecraft would orbit about a point determined by the relative magnitude of the earth gravity forces and the solar light pressure forces. The amount of displacement north or south of the equatorial plane is limited to a few hundred kilometers for unfurlable Kapton sails and a few thousand kilometers for very thin solid aluminum film sails. By perforating the sail, however, we can improve the displacement distance significantly. Figure 7 shows a geostationary orbit that is levitated by the constant solar pressure 13,000 km northward from the equatorial plane, about twice the radius of the earth.[29]

The levitated orbit is noticeably displaced in the direction opposite to the sun. (This effect was noticed on the Echo balloon satellite.) By varying the sail angle with the seasons, the levitated orbit can be kept synchronous with the earth's rotation. The time of year chosen for Figure 7 is at summer solstice, where the sun angle is the worst for providing northward thrust. In this worst case example, the position of the satellite is not truly geostationary. As seen from the north pole, it moves ±1.7° about its nominal elevation angle of 9.3°. The development of perforated solar sails and their use to create levitated orbits would not only relieve the pressure on the limited number of positions along the equatorial geostationary orbit, but would for the first time provide a true geostationary communications capability to the militarily important polar regions of the earth.

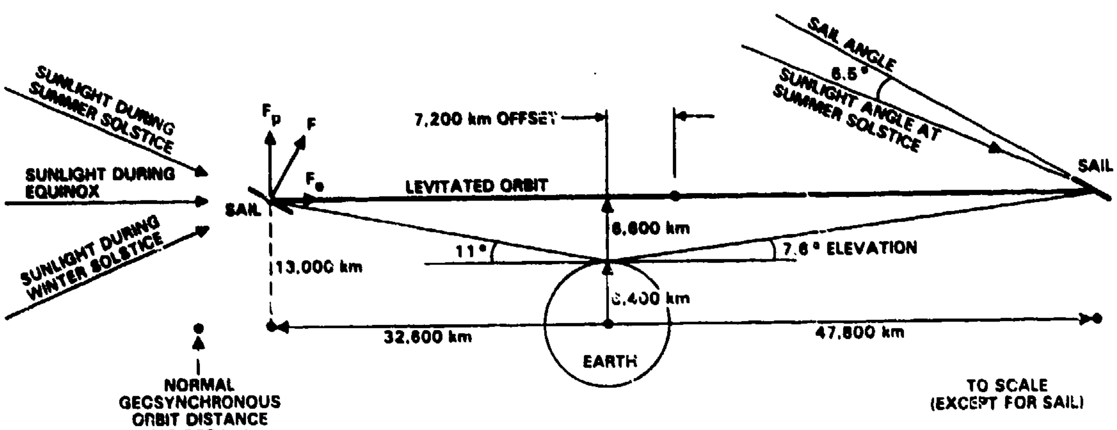

Figure C-7. Polar Levitated Geostationary Orbit

It is not necessary to require the use of ultralight perforated sails to carry out exotic missions that are not conceivable using rocket propulsion. Since the solar sail never runs out of fuel, it can be used to hover in space, completely ignoring the usual constraints of orbital mechanics. One example is a shadow sitter that stays permanently in the shadow cone of a planet.[30] As shown in Figure 8, the shadow cone of the earth extends out to 217 earth radii. An Eclipsat with a sail made in the shape of a ring could then be placed to sit on the shadow cone, with its payload hanging in shadow. From this vantage point, the payload would see the sun in a constant perfect total eclipse. From here scientific instruments could continuously monitor the solar corona for solar storms of importance not only to solar physics but to communications and space travelers. Since the gravity field of the earth at 217 earth radii is only 20 microgees, even a sail with a 1976 technology areal density of 1 g/m^2 could levitate a hefty scientific payload.

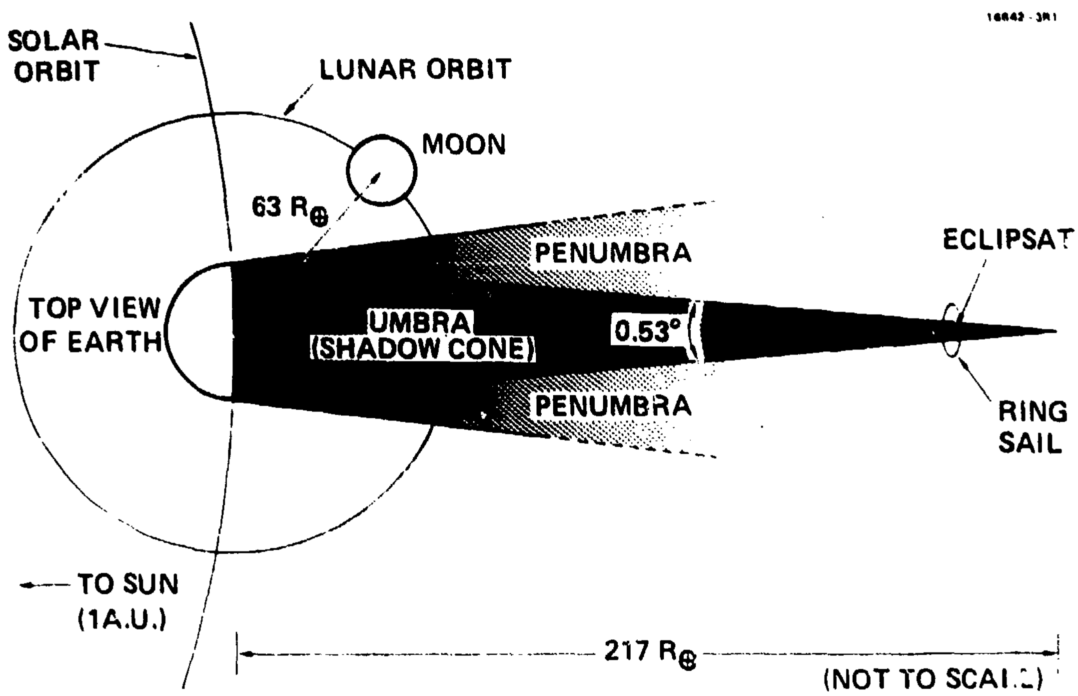

Figure C-8. Eclipsat

Since the source of the propulsion for solar sails is the sun, they naturally work better closer to the source. In addition, the gravity field of the sun varies as $1/R^2$ and the solar flux varies as $1/R^2$. Thus, once we get away from the gravity field of the planets, the performance of solar sails in the gravity field of the sun is independent of distance. For a sail to be able to hover in the sunlight from the sun, its mass to area ratio must be less than a certain value. This is determined by the balance between gravitational attraction and light pressure repulsion.

$$F=GMm/R^2=2P/c=2SA/c$$

where M is the mass of the sun, m is the mass of the sail, and the total light power P is given by the solar flux S times the area A of the sail. For the distance of the earth from the sun $R=1\ AU=1.5\times10^{11}$ m, the solar flux $S=1400\ W/m^2$. With these numbers we can calculate the mass per unit area of sail and payload needed to just levitate the sail in the gravity field of the sun.

$$m/A=1.6\ g/m^2$$

So it doesn't take a high performance sail to operate around the sun.

One exotic mission for solar sails around the sun would be to set up a set of scientific Sunwatchers to continuously monitor the changes in the solar surface. As is shown in Figure 9, we could place a number of high temperature sails in hovering orbits around the sun. One could be placed over each pole to constantly monitor what is going on in the polar regions.[28] Others could be placed in solar synchronous orbits with a period matching that of the solar rotation at the latitude of interest. Note that because of the constant propulsive thrust capability of the solar sails, the resultant force vector can be used to cancel out a portion of the solar gravity pull, making the effective net attraction any value that you want, independent of the orbital radius. Thus, the orbital period can be decoupled from the orbital radius, and the 25 day solar synchronous orbit can have any altitude from the solar surface that is convenient. (Unfortunately this trick won't work for communication satellites around the earth. The sun is off to one side of the earth and not at the center of the earth.)

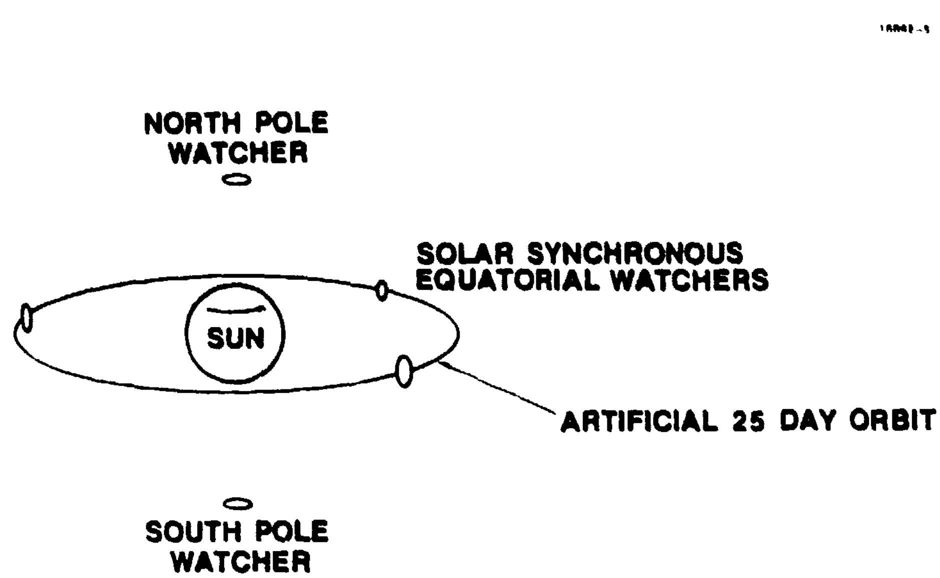

Figure C-9. Sunwatcher Sail System

These are only a few of the exotic missions that can be performed with the only rocket ship that never runs out of fuel and lasts almost forever. To obtain most of the more interesting missions, however, will require the development of high performance sails, probably perforated thin films. What is needed are good measurements of the performance of real films as a function of film thickness, hole size, and ratio of hole area to total area. We also need engineering studies of how these films might be fabricated, deployed, and supported during operation.

LASER PUSHED LIGHTSAILS FOR INTERSTELLAR TRANSPORT

As spaceships, solar sails are unique in that they require no reaction mass, no energy source, and no engine, and can operate continuously without refueling. At first glance, they might seem ideal for that most exotic of missions, traveling to the stars. Since solar sails must depend upon sunlight for their power, however, they are limited to operations in the inner part of the solar system since the sunlight falls off in intensity with distance. There is another kind of light that can be beamed over long distances with little decrease in intensity with distance, coherent laser light. Thus, one method for traveling to the stars would use large lightsails pushed by the photon pressure from a large laser array in orbit around the sun.[31] It turns out that using this technique, we can build a manned spacecraft that not only can travel at reasonable speeds to the nearest stars, but can also stop, then return its crew back to earth again within their lifetime. It will be some time before our engineering capabilities in space will be up to building the laser system needed, but there is no new physics involved, just a large scale version of known devices.

The lasers would be in orbit around Mercury[30] to keep them from being "blown" away by the reaction from their light beams. They would use the abundant sunlight to produce coherent laser light, which would be collected into a single coherent beam and sent to a transmitter lens out between Saturn and Uranus. The transmitter lens would be a fresnel zone plate lens tuned to the laser frequency and consisting of micron-thin plastic rings alternating with empty rings. It would be 1000 kilometers in diameter and weigh about 560,000 tonnes. A lens this size can send a beam of laser light over 40 lightyears before the beam starts to spread.

The first use[31] for this lens would be to send a one-way unmanned flyby probe mission to the nearest star. This mission would be limited in acceleration by the maximum temperature that the sail could take. We will assume a maximum operating temperature of 600 K, and a partially transparent 16 nm thick aluminum sail with a reflectance of 0.82, absorptance of 0.135, and emissivity of 0.06. The areal density of the sail, structure, and payload is assumed to be 0.1 g/m^2, giving a thermally limited acceleration of 0.36 m/s^2 (0.036 gees). If we assume a minimal mass probe of 1000 kg (roughly one-third each of sail, structure and payload), then the diameter of the sail is 3.6 km. The power needed to push this sail at 0.36 m/s^2 is 65 GW. While this is a great deal of laser power, it is well within future capabilities. If the acceleration is maintained for three years, the interstellar probe will attain the velocity of 3.4×10^7 m/s (0.11 c) at the distance from the lens of 1.6×10^{15} m (0.17 lightyears). At this distance, the spot size of the laser beam as focused by the 1000 km diameter lens is 3.8 km, so that nearly all the laser power is still being captured by the 3.6 km diameter sail. The laser is then turned off and the interstellar probe coasts to its target, reaching α Centauri at 4.3 lightyears distance in 40 years from launch.

If the reports from the interstellar probes are favorable, then the next phase would be to send a human crew on an interstellar exploration journey. More than just the nearest star system will ultimately need to be explored, so we will design[31] the laser lightsail system to have the capability to make roundtrip journeys out to 12 lightyears, so we can visit Sol-like stars such as τ Ceti and ϵ Eridani. As is shown in Figure 10, we will assume a lightsail that is 1000 km in diameter and made of thin aluminum film stretched over a supporting structure. The total weight will be 80,000 tonnes, including 3,000 tonnes for the crew, their habitat, their supplies, and their exploration vehicles. The lightsail would be accelerated at 0.3 gravities by 43,000 TW of laser power. (For comparison, the earth now produces 1 TW of power.) At this acceleration, the lightsail will reach a velocity of half the speed of light in 1.6 years. The expedition will reach ϵ Eridani in 20 years earth time and 17 years crew time. At 0.4 lightyears from the star, the 320 km rendezvous portion of the sail detaches from the outer ring sail and turns to face the large ring mirror. The laser light from the solar system reflects from the ring sail acting as a mirror. The retro-reflected light decelerates the smaller sail and brings it to a halt in the ϵ Eridani system. After exploring the system for a few years, it will be time to bring the crew back. To do this we separate out the 100 km return sail from the 320 km rendezvous sail. The laser light from the solar system hits the rendezvous sail, is reflected back on the return sail, sending it on its way back home. As the return sail approaches the solar system 20 earth-years later, it is brought to a halt by a final burst of laser power. The members of the crew have been away 51 years (including 5 years of exploring), have aged 46 years, and are ready to retire and write their memoirs.

SUMMARY

Although chemical rockets have served us well in the 20th Century, more exotic forms of propulsion will be needed for our adventures in the 21st Century and beyond. Fortunately, there seem to be many new ideas that promise to produce amazing advances in our capabilities to move through space. Even if only some of them come true, we soon will be island kings of our little archipelago of planets in the solar system and starting to dip our toes in the oceans of interstellar space. Buck Rogers and the 25th Century may be closer than we think.

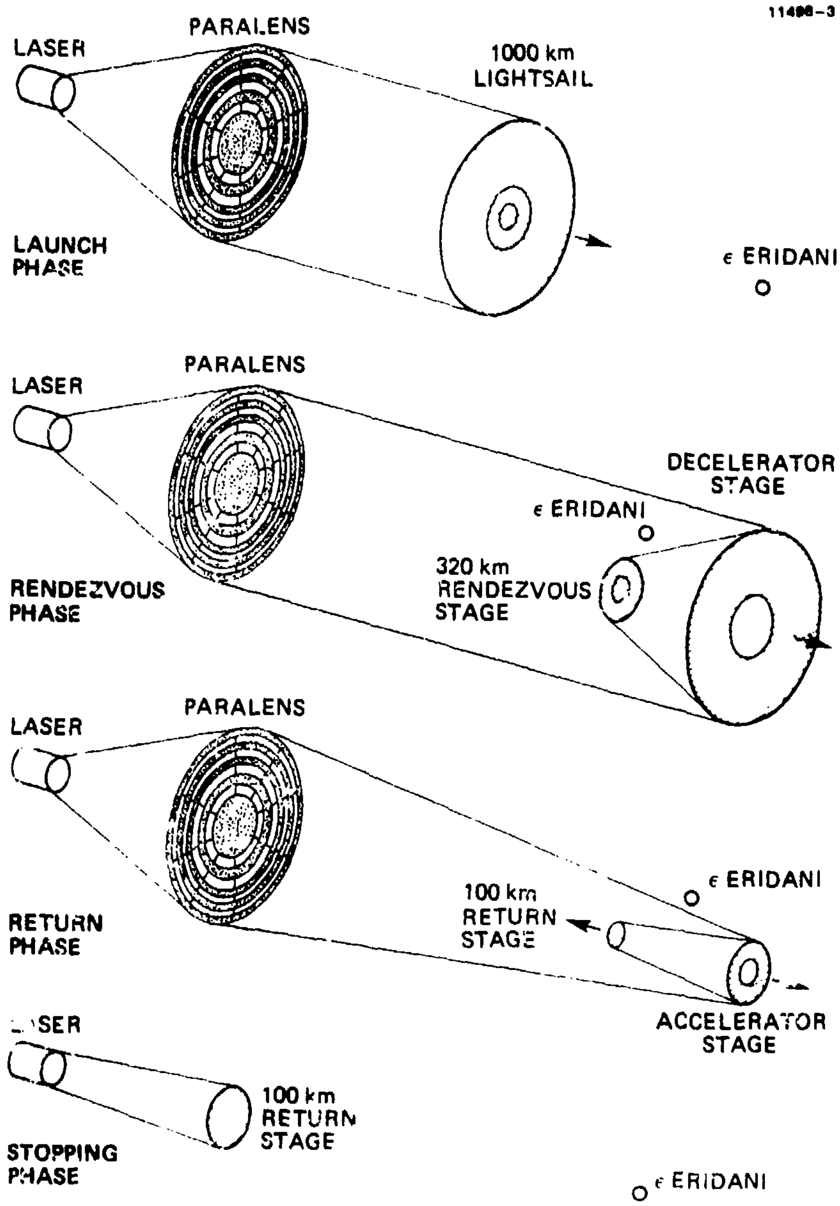

Figure C-10. Roundtrip Interstellar Travel Using Laser Pushed Lightsails.

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APPENDIX D

PROSPECTS FOR ANTIPROTON PRODUCTION AND PROPULSION

PROSPECTS FOR ANTIPROTON PRODUCTION AND PROPULSION

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PROSPECTS FOR ANTIPROTON PRODUCTION AND PROPULSION

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ABSTRACT

Antiproton annihilation propulsion is a new form of space propulsion, where milligrams of antiprotons in the form of frozen crystals of antihydrogen are used to heat tons of reaction fluid to high temperatures. The hot reaction fluid is exhausted from a nozzle to produce high thrust at high exhaust velocity. This paper summarizes the results of a continuing study to determine the physical, engineering, and economic feasibility of antiproton annihilation propulsion. The conclusion of the study to date is that antiproton propulsion is feasible, but expensive. Because the low mass of the antihydrogen fuel and its storage container more than compensates for the high price of antiprotons, comparative mission studies show that antihydrogen fuel can be cost effective in space, where even normal chemical fuel is expensive because its mass must be lifted into orbit before it can be used. Antiprotons are already being generated, captured, cooled, and stored at a number of particle physics laboratories around the world, albeit in small quantities. This paper outlines some ideas for improving the generation efficiency of antiprotons and describes techniques for the cooling, trapping, long-term storage, and effective utilization of milligram quanti[illegible] of antihydrogen for space propulsion. Converting the an[illegible]tons into antihydrogen is a non-trivial problem. One of the [illegible]ore promising techniques involves the use of hydrogen cluster ions. Since the formation of (anti)hydrogen from (anti)protons and (anti)electrons through the cluster ion process will be the subject of the rest of the papers in this workshop, it will not be addressed in this paper.

INTRODUCTION AND SUMMARY

In antiproton annihilation propulsion, milligrams of antihydrogen will be used to heat tons of reaction fluid to high temperatures. The hot reaction fluid will then be exhausted from a nozzle to produce high thrust at high exhaust velocity (100 to 350 km/s). Antiprotons are the preferred form of antimatter for propulsion. Unlike antielectrons (positrons), antiprotons do not completely convert into gamma rays upon annihilation. Instead, two-thirds of the annihilation 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.

Picogram quantities of antiprotons are already being generated, captured, cooled, and stored in magnetic storage rings at a number of particle physics laboratories around the world. The facility at CERN in Switzerland[1] has been producing picograms of antiprotons per day since 1982. The facility at Fermilab in the USA[2] came on line in 1985, but there are no plans to decelerate the antiprotons to subrelativistic energies. The facility at IHEP in Novosibirsk, USSR[3,4] is still in the planning stage.

As is shown in Figure 1, normal matter protons are accelerated to relativistic velocities in a proton synchrotron accelerator until their kinetic energy (26 to 120 GeV) is many times greater than their rest mass energy (1 GeV). The high energy proton beam is sent into a heavy metal target where the kinetic energy is converted into a spray of photons and particle-antiparticle pairs, a small fraction (<5%) of which are proton-antiproton pairs. A fraction (<30%) of the relativistic antiprotons (3 to 50 GeV) are at a small enough angle to be brought to a focus by a magnetic focusing lens. Of these, a very small fraction (<1%) have the proper momentum to be captured by a magnetic ring. The pulses of captured antiprotons are debunched and cooled using rf fields, then decelerated to subrelativistic energies (<50 to 300 MeV) where they are further cooled, accumulated, and stored for hours or days at a time until they are needed for high energy proton-antiproton collision experiments or low energy antiproton annihilation experiments.

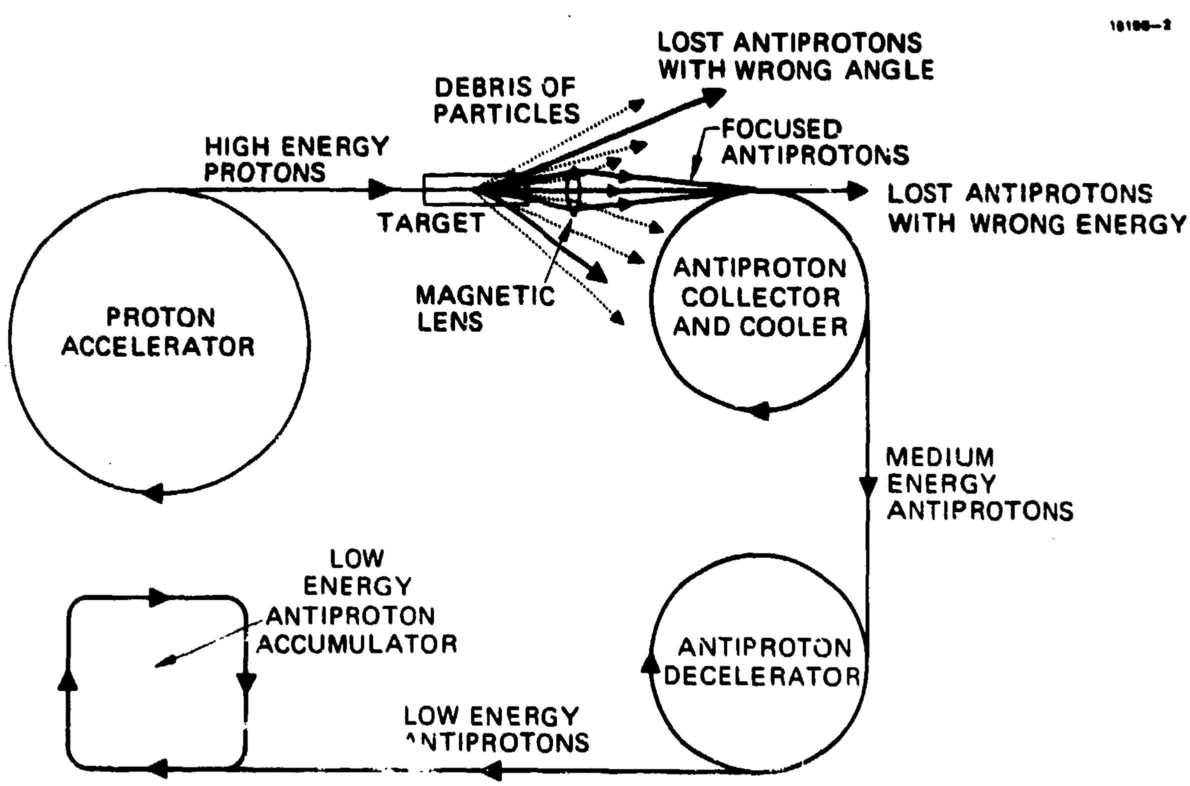

Figure D-1. Present method for collecting antiprotons.

We will assume the reader is aware of this ongoing work on the production of antiprotons at the various particle physics laboratories around the world. In this paper we will concentrate on the less well known techniques for using antiprotons for propulsion, improving the antiproton production efficiency from picograms per day to milligrams per day, briefly discuss the problems of turning the antiprotons into antihydrogen, and then show how the antihydrogen can be held for long periods of time in relatively compact storage traps until ready for use.

ANTIHYDROGEN PROPULSION

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[5] assumed that the antimatter would be in the form of positrons, which interact with electrons to produce 0.511 MeV gamma rays. The antiproton is more suitable than the positron for propulsion systems. The annihilation of an antiproton with a proton does not produce gamma rays immediately. Instead, the products of the annihilation are from three to seven pions. On the average there are 3.0 charged and 1.5 neutral pions.[6] As is shown schematically in Figure 2, the neutral pions have a lifetime of only 90 as and almost immediately convert into two high energy (200 MeV) gamma rays. The charged pions have a normal half-life of 26 ns, but because they are moving at 94% the speed of light, their lives are lengthened to 70 ns. Thus, they travel an average of 21 m before they decay.

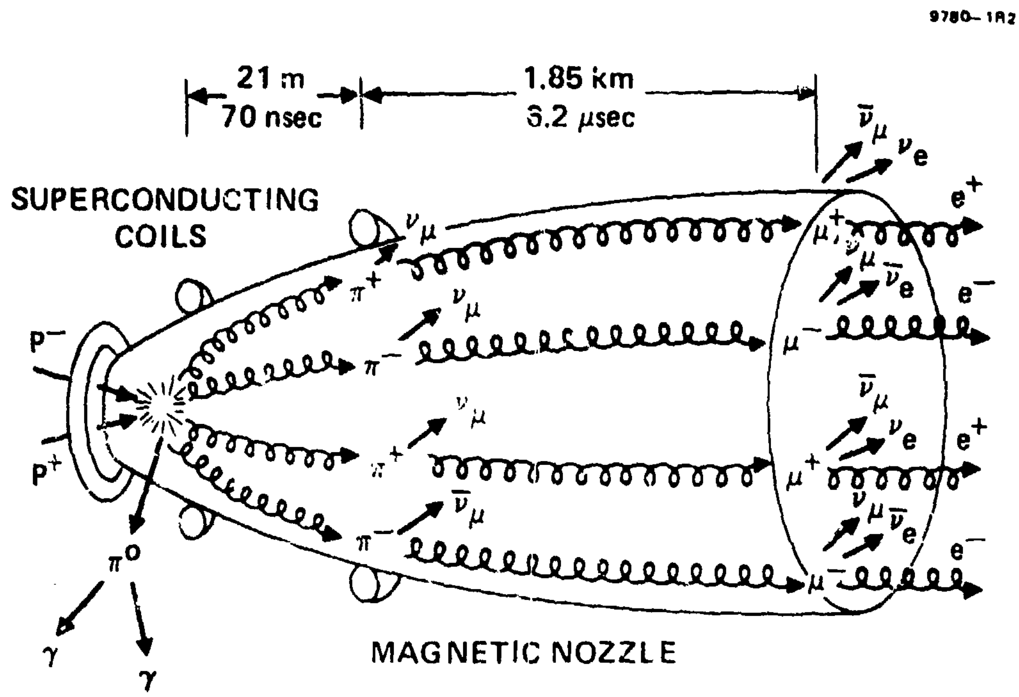

Figure D-2. Schematic of an idealized antiproton rocket.

This interaction length is long enough that either magnetic fields can be used to redirect the isotropic microexplosion into a directed flow of charged pions to provide thrust or the charged pions can be used to heat reaction mass. 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. The charged muons then decay into energetic charged electrons and positrons, which can be utilized to obtain more thrust. Thus, if milligrams of antiprotons could be made and stored, then, according to known physical principles, they can be used as a highly efficient propulsion energy source.

Because of the extreme difficulty in obtaining significant quantities of antimatter, the idea of an antimatter rocket has usually been relegated to the category of "science fiction". Recent progress in particle physics on methods for obtaining intense antiproton beams, however, has caused those in the space propulsion community to take another look at the concept of antimatter propulsion to see if the concept can be removed from the "science fiction" category to the "technically difficult and very costly" category, at which point the military services or NASA could begin considering its use. The last seven years have seen the presentation of a number of papers on antimatter propulsion,[7-14] A study was also recently undertaken to determine the physical, engineering, and economic feasibility of antiproton powered propulsion.[15] The conclusion of the study was that antihydrogen propulsion was feasible, but expensive.

ANTIMATTER PROPULSION MISSIONS

The availability of antimatter as an energy source for space propulsion will revolutionize space travel. Many of the present assumptions that are implicit in the design of a mission will no longer be valid, and mission designers will have to develop a new set of assumptions to replace them. For example, the concept of mass ratio and staging mass fractions plays an important part in the present design of missions. Once a mission has been defined, there is a certain characteristic velocity V for that mission and once the fuel is chosen, there is a fixed exhaust velocity v available from that fuel. The total mission mass ratio R is then automatically determined by the relation:

$$R = \frac{m_v + m_p}{m_v} = e^{V/v}$$

where m_v is the mass of the empty vehicle (including payload) delivered to the destination and m_p is the mass of the propellant exhausted at velocity v. Thus, every different mission with a different characteristic velocity requires a different mass ratio and a different vehicle design. Also, if the mission characteristic velocity exceeds five times the exhaust velocity, the mass ratio becomes greater than 100, and there is a tendency to say that the mission is "impossible".

With antimatter powered rockets, the exhaust velocity can be tailored to match the mission characteristic velocity, thus minimizing the mass ratio and mission cost. It has long been known[16] that the mass ratio of an optimized antimatter rocket never exceeds 5:1, and mass ratios that minimize total mission cost are typically 2.5:1 for any mission characteristic velocity[13]. Since the amount of reaction mass needed remains a constant, the same vehicle can be used for all missions, with the only difference being the amount of antimatter used. With antimatter rockets, mission trajectories will no longer be modified Hohmann transfers, but nearly straight lines. Manned missions to Mars will no longer take years of time, but months of time[14], with significant savings in vehicle and ground support costs.

Research on antiproton annihilation propulsion technology is admittedly very high risk. The extremely high payoff in fast, efficient space propulsion, however, makes it worthwhile to spend a significant amount of effort to determine the feasibility of the concept. In addition, there seems to be a paucity of alternate propulsion concepts that can achieve the same results of high propulsion efficiency, low system mass, comparatively low cost, and short mission times.

IMPROVING ANTIPROTON PRODUCTION EFFICIENCIES

There are a number of obvious ways to improve the efficiency of antiproton production over the present methods. It should be realized that the present production facilities were designed under a number of restrictions. They had to use existing proton accelerators, fit onto the existing sites, and not use too much time on the main research machine. In our recent study[15] a good part of our effort was to determine the reasons behind the low efficiencies of the present facilities. Some of the low efficiencies are inherent, such as the number of antiprotons per proton from a target. Most of the other low efficiencies are just artifacts of the particular choices forced on the particular facility, and there are obvious ways to improve these efficiencies by large factors.

When the present facilities for generating antiprotons[1-4] were constructed, they had to use existing proton accelerators available at the site. The operating energies of these accelerators are known to be far from optimum for efficient production of antiprotons. It can be shown[15] that the maximum energy efficiency production rate occurs for an incident proton energy of 200 GeV and is 0.085 antiprotons/proton. 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. Although the number of antiprotons produced continues to increase as the incident proton energy is increased, above 200 GeV the gain in antiproton annihilation energy obtainable is not enough to offset the increased proton energy required.

IMPROVING ACCELERATOR EFFICIENCY

The present machines that are used for accelerating protons to relativistic speeds are synchrotrons. The synchrotron provides the particle physicist with high-energy protons at a very precisely known energy. It is the ideal tool for the study of elementary particle physics. The average current that the synchrotron can handle is small, however, and the energy efficiency is only a few percent. The linear accelerator or linac is an alternate machine for producing high-energy protons that can handle high average currents and has high energy efficiency. By using the alternating gradient focusing concept, it has become possible to accelerate high current beams to very high energies. The energy limit is economic, not technical. It is known that machines can be built to handle peak currents of over 250 mA, since that has been demonstrated in the first section of the linac injector at Fermilab, which is the only section where current limitations would occur. Acceleration to higher energies only requires more rf acceleration sections.

With the availability of new high efficiency (75%) klystrons, the ac "wallplug" power to proton beam power efficiencies of a linac could exceed 50%. The Chalk River, Canada linac program[17] has been studying 100% duty factor linacs, with the goal of producing a linac capable of of 300 mA average current at 1 GeV (0.3 GW beam power) for use in an accelerator breeder. The acceleration limit of a linac (the energy increase per meter) is determined by the sparking limit in the cavity. The sparking limit is inversely proportional to the wavelength. Present 200 MHz machines usually operate at 1 MeV/m but there are designs for higher frequency machines that will operate at 5 MeV/m. A 5 MeV/m linac for generating a 200 GeV proton beam would be 40 km long. This is a little longer than the 28 km LEP ring presently under construction at CERN and 1/5th the size of the 200 km Supercollider being proposed as the next large particle accelerator in the USA. If run at a power level of 10 GW, the proton current required would be only 50 mA. By separating out the antiprotons coming from the target and dumping the remaining particles into an electronuclear breeder reactor loaded with unenriched uranium, such a factory would require no outside power source and would essentially be turning depleted uranium into plutonium and antiprotons.

IMPROVING ANGULAR CAPTURE EFFICIENCY

The present angular capture efficiencies of the magnetic lens collection systems are already quite good, with up to 30% of the antiprotons collected and directed into the aperture of the collecting ring. The present designs, however, were optimized for the antiproton energies expected at the particular facility and the particular conditions in the target area. All of the studies to date have assumed that only a single, on-axis lens would be used to capture the antiprotons. Because the antiprotons are being emitted over a wide angle, this immediately leads to the requirement of a short focal length for the lens so it can capture these wide angle antiprotons. Research needs to be done on the feasibility and comparative merits of an array of lenses. Since each lens has to capture only the antiprotons in a small portion of the emitted beam solid angle, the focal length requirements can be relaxed, making the lens design easier. The support hardware for the lenses will cause interception losses, however, and realistic tradeoff studies need to be done between the number of lenses and the lens design parameters. If a multiple lens approach looks desirable, then invention is needed on low-loss devices for separating the wide angle antiproton beam into multiple beams to minimize the interception losses of the multiple lens hardware.

Present magnetic lens designs, such as the lithium lens[18], require the antiproton beam to pass through the material of the lens. This causes significant losses in the antiproton spectrum. This is not true for the magnetic quadrupole lens, but it does not focus well in all orientations. New lens concepts are needed with low loss and good focusing. Another method for construction of a magnetic lens similar to that of the lithium lens would be to carry the current for the lens in a cylinder of ionized plasma[19] instead of lithium metal. The problem of current or beam heating of the lens would be gone and it is likely that absorption of the antiprotons in the lens would be less. A plasma lens would also have problems, such as the various plasma instabilities that would be driven by the high currents needed.

The present single magnetic lens concepts have already achieved angular capture efficiencies of 33% or greater and there are many ideas for new lens concepts with greatly improved performance. It is reasonable to expect that after modest investment in invention, engineering, and testing, there should be new magnetic lens designs capable of capture angles of 60 mrad and capture efficiencies of 85% or greater.

IMPROVING MOMENTUM CAPTURE EFFICIENCY

When the antiprotons come from the target, they have a wide spread in momentum as well as angle. It is this wide spread in antiproton momentum and the difficulty of making an antiproton collection ring with a wide momentum acceptance that leads to the extremely low inefficiencies in present antiproton "factories". For example, at CERN, the present momentum acceptance in the Antiproton Accumulator is only dp/p=1.5%. For a peak momentum of 5 GeV/c, this translates into a momentum bite of only 0.05 GeV/c. Thus, only 1% of the 5 GeV/c half-width of the antiproton momentum spectrum is captured. If we assume that an antiproton factory has an incident proton beam at 200 GeV energy and a 60 mrad angular acceptance, then the flux of antiprotons per proton per unit antiproton momentum is shown in Figure 3.[20] The antiproton flux peaks at 12.5 GeV/c antiproton momentum and spreads from 1 GeV/c to 50 GeV/c, with a half-width of 22 GeV/c. The present state-of-the-art in collection rings for antiprotons is a momentum acceptance of about 6%. Even if this could be raised to 3%, the momentum bite at an antiproton momentum of 12.5 GeV/c would still be only 1 GeV/c and would capture only 4.5% of the antiprotons.

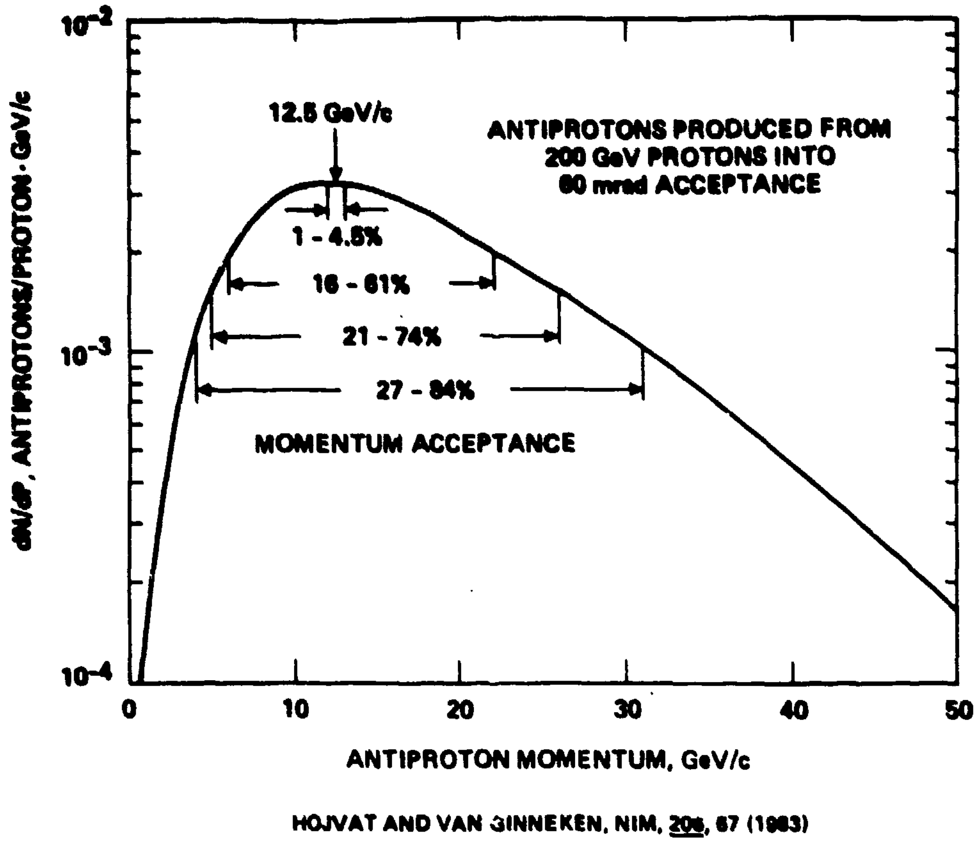

Figure D-3. Antiprotons vs. momentum spread.

The obvious solution is to build a multiplicity of rings. They would be identical copies and share the same tunnel (since tunnel costs are a major portion of the cost of a ring). Each ring would have the strength of the magnetic fields in its bending magnets set at a different level to keep a different antiproton momentum circulating through its vacuum pipe. If each ring could handle a momentum bite of 1 GeV/c, then as we see in Figure 3, 16 rings could capture 61% of the antiproton momentum spectrum and 27 rings could capture 84% of the antiprotons.

Separating the antiproton beam into different momentum buckets should not be difficult. A magnetic focusing lens has chromatic aberration. Antiprotons with different momenta come to a focus at different distances from the focusing lens. A string of diverter magnets can deflect the different antiproton momenta in different directions, where they can be channeled to the proper collecting ring.

SYSTEM EFFICIENCY ESTIMATES

From the previous sections we can see that there are a number of ways to improve the efficiency of antiproton production over the present techniques. The first obvious improvement is to use a higher proton energy so that more antiprotons are produced in the target. As is shown in Table 1, by going to 200 GeV, the number of antiprotons produced can be increased by a factor of 20 from the 3.8×10^{-3} $\bar{p}$/p at CERN to 8.5×10^{-2} $\bar{p}$/p. The present magnetic lenses are relatively efficient in capturing the resulting antiprotons in angle. Yet by improving the design and going to multiple lens collectors, we should be able to improve the angular capture efficiency by a factor of 3 or 4 to 85%.

Another place where improvement can be made is in the momentum capture efficiency. The single ring collectors at CERN[1], Fermilab[2], and IHEP[3,4] are severely limited by difficulties with matching the ring acceptances to the lens emittances. With a large enough tunnel and enough money to build copies of the collectors, each tuned to accept a different momentum range, it should be possible to improve the capture efficiencies significantly. Whether it will be possible to go from the present few percent to a desirable 85% is unknown.

There are many losses as the antiproton beam is generated, collected, and switched around from one device to another. The handling efficiencies in the present facilities are not bad, but improvement in this area is also needed. As we can see from Table 1, if all these efficiencies can be achieved, the total production efficiency of antiprotons can be raised from the present 4×10^{-7} $\bar{p}$/p at CERN by more than five orders of magnitude to 5×10^{-2} $\bar{p}$/p.

Table D-1. Antiproton Production Efficiencies

	CERN	Fermilab	Goal
Incident Proton Energy (GeV)	26	120	200
Generation Efficiency ($\bar{p}$/p)	0.4%	4.7%	8.5%
Angular Capture Efficiency	20%	30%	85%
Momentum Capture Efficiency	1%	1.2%	85%
Handling Efficiency (est.)	5%	18%	80%
Total Prod. Efficiency ($\bar{p}$/p)	4×10^{-7}	3×10^{-5}	5×10^{-2}

TRAPPING OF ANTIPROTONS

The present method for storing antiprotons uses magnetic storage rings, which keep the antiprotons circling in a beam at some fixed momentum. These large, heavy, magnetic storage rings are obviously unsuitable for propulsion applications. A number of experimenters have proposed to decelerate the antiproton ions down to almost zero velocity and put them into a Penning trap.

The first to accomplish this feat was a group led by Prof. G. Gabrielse from the University of Washington,[21] who has a paper describing their experiment elsewhere in these proceedings. They used a cryogenic Penning trap modified by thinning the center portion of one of the cap electrodes down to about 0.25 mm. This thin portion was used to degrade the energy in a pulse of antiprotons extracted from the low energy antiproton ring (LEAR) at CERN. The velocity of the antiprotons was brought down to nearly zero so the antiprotons could be captured in the trap. The intention of the group is to return to CERN in 1987 to trap just a few antiprotons and measure the mass of the antiproton to high precision. A group led by M. Hynes at Los Alamos National Laboratory is more ambitious[22]. They are fabricating a radio frequency quadrupole (RFQ) decelerator that will decelerate a beam dump of antiprotons from LEAR down to the trap energy and deposit up to 10^{10} antiprotons in their Penning trap.

CONVERSION OF ANTIPROTONS TO ANTIHYDROGEN

For propulsion applications it would be desirable to minimize the size and mass of the antimatter container. To do this it will be necessary to store the antiprotons as some form of antihydrogen rather than as antiproton ions. The first step is to convert the antiprotons into atomic antihydrogen by adding a positron. A straightforward approach to the production of antihydrogen from these trapped antiprotons would be to convert the Penning trap into one that would hold and cool both positive and negative ions. A simple example is the rf Paul trap, which can hold both antiprotons and positrons, and cool them until their relative velocities are low enough that the conversion to antihydrogen takes place naturally. The use of rf modulation or laser radiation to enhance the various reactions needs to be studied. Also, the effectiveness of magnetic fields or laser beams[23] to trap and manipulate the neutral antihydrogen atoms and ions needs to be determined.

CLUSTER ION FORMATION OF ANTIHYDROGEN ICE

The objective of this workshop is to study the feasibility of the growth of amorphous or crystalline antihydrogen through the cluster ion process. The important feature of the cluster ion process is that the growing cluster always maintains a charge and thus can easily be kept in an electromagnetic trap. It is hoped that macroscopic crystals can be grown in this fashion, since it will certainly be simpler than trying to grow neutral antihydrogen ice crystals using laser trapping and cooling[23] or some other yet-to-be-discovered process.

Since other reports in this workshop proceedings will cover the cluster ion growth and cooling processes in considerable detail, I will not include a discussion here, but will assume that the growth has been successful and that we have made macroscopic amorphous or crystalline balls of antihydrogen ice. The antihydrogen ice should be generated at very low temperatures (<2 K) to prevent evaporation loss and should be large enough to scatter infrared light so their position can be determined. The resulting ice particles will mass from nanograms (10^5 J of equivalent energy) to milligrams (10^{11} J of equivalent energy).

LEVITATION OF ANTIHYDROGEN ICE

The techniques for the formation of solid antihydrogen may turn out to be relatively simple. More likely, however, the effort may require large, heavy, complex equipment requiring large amounts of power. Once the small microcrystals or larger ice balls of antihydrogen ice are formed, however, they can be transferred to a compact, lightweight, storage and transport system that uses simple magnetic or electric traps for levitation. The magnetic susceptibility of molecular hydrogen depends upon its state. The orthohydrogen molecule has both of its protons with their magnetic moments pointing in the same direction, so it has a positive magnetic moment. The parahydrogen molecule has its two protons and its two electrons with their spins oriented in opposite directions so the particle spins cancel out. This gives the parahydrogen molecule a negative or diamagnetic susceptibility. Diamagnetic substances are attracted to the minimum in a magnetic field. Even with a purely static magnetic field, the configuration is stable, unlike levitation systems based on repulsion of paramagnetic or ferromagnetic materials, which are unstable.

The magnetic susceptibility of solid parahydrogen has not yet been measured. The theoretical prediction of the magnetic susceptibility of a one-gram formula weight of molecular hydrogen is -3.98×10^{-6} cgs units.[24] This is to be compared to a value of -6.0×10^{-6} cgs for graphite. There have been many demonstrations of the stable levitation of grams of graphite using nonsuperconducting magnets. In one example, a ring shaped rotor weighing 3.843 g and containing only 0.933 g of graphite was levitated in the 0.2 cm gap between two opposed ring shaped room temperature permanent magnets with a magnetic field of 11,600 G.[25]

One configuration for a magnetic trap that would be compatible with a cryogenically cooled vacuum chamber would be a pair of superconducting rings carrying opposed persistent currents. This passive magnetic levitation technique is the preferred suspension method since it would be safer than any active levitation technique, as well as making the storage and transport container extremely simple, compact, and independent of electric power.

An alternate method of levitating antihydrogen ice is to use active electrostatic levitation between two servo-controlled electrically charged plates. The ice particles need to be slightly charged. This can be accomplished either by charging the ice positive by addition of extra positrons or charging it negative by driving off the positrons with ultraviolet light. One example of such an electrostatic trap has been constructed at the Jet Propulsion Laboratory.[26] The trap has levitated a 20-mg ball of water ice in the one gee field of the earth. The density of water at 1.0 g/cc is 13 times that of antihydrogen ice at 0.0763 g/cc. Thus, the present JPL trap with its present voltage levels could levitate a 1.5-mg ball of antihydrogen ice of the same size, surface area, and surface charge at a vehicle acceleration of 13 gees.

STORAGE OF ANTIHYDROGEN ICE

As has been shown in previous sections, it should be possible to form and levitate antihydrogen ice. Since laser cooling[23] will leave the antihydrogen at a temperature well below 1 K, the antihydrogen ice will start out cold. The vapor pressure of antihydrogen[27] at 1 K is only 8.3×10^{-39} Torr, so if kept below this temperature there is essentially no sublimation. The vapor pressure rises exponentially with the inverse of the temperature, however, so at 2 K it has risen to 4×10^{-18} Torr, where the sublimation rate is about 1000 (anti)molecules per second from a milligram-sized ball, while at 4 K it is 2×10^{-7} Torr, where sublimation is rapid. To keep the sublimation rate of the antihydrogen down to controllable levels, its temperature should be kept below 2 K. The walls of the storage and transport container should also be cooled to well below liquid helium temperatures to keep the walls from outgassing. New, continuously operating rotary paramagnetic salt refrigerators in a compact package are now available[28] that can pump 1.8 W at 1.8 K, so the mass of these antimatter "fuel tanks" should not be a problem.

Even if the antihydrogen and the walls are kept cold, there will always be a few stray antihydrogen molecules leaving the ice ball and annihilating on the container walls, while there will also be a few stray outgassing hydrogen molecules or other normal molecules knocked off the container walls by those annihilation processes or cosmic rays that would drift across the chamber to annihilate on the surface of the antihydrogen. Each molecular annihilation event will produce on the average six 200 MeV gamma rays, six 250 MeV charged pions, and four 0.511 MeV gammas from the annihilation of the positrons and electrons.

For 200 MeV gamma rays, the attenuation coefficient in matter is roughly constant at 0.1 cm^2/g. Since the density of antihydrogen is 0.0763 gm/cm^3, the attenuation per unit path length is only 0.0076/cm. Thus, instead of causing intense local heating, most of the gamma rays would pass right through a milligram sized iceball and continue on through the container wall to deposit their energy in the outside shield. Only 74 fJ or 460 keV of energy is deposited in the antihydrogen iceball. For the 250 MeV charged pions, the stopping power is essentially flat at 15 MeV/(g/cm^2). The charged pions will leave only 55 fJ or 340 keV of energy in the antihydrogen and deposit most of their energy outside. Thus, an annihilation that takes place on the surface of an antihydrogen iceball will only deposit 0.5 pJ of energy, or a picowatt heat input for two annihilations/second.

Obtaining a better estimate of the real vapor pressure inside a cryogenically cooled chamber will require research. We have evidence that the vacuums must be fairly good since a single positron has been kept in a 4.2 K Penning trap for a month.[29] But the annihilation cross section for a free positron and a bound electron at these very low energies is not known well enough to establish a firm lower bound on the vacuum level in the trap. Plans are presently underway[21] to trap a few antiprotons from the Low Energy Antiproton Ring at CERN in a cryogenically cooled Penning trap in order to measure the antiproton mass to high accuracy. If the antiprotons survive in these traps for long periods of time, then this should also provide estimates of the residual vapor pressure in these traps.

Despite all precautions, some heat will get to the antihydrogen ice and methods must be found to remove that heat without physically contacting the antihydrogen. One possibility is to use radiation cooling to the container walls. Cluster ions, because of their complex structure have a complex infrared spectrum. This should aid in cooling the cluster during formation. One essential aspect of cluster ion research should be the measurement of the infrared spectra as a function of cluster ion size and composition. This data can then be used to determine whether radiation cooling will be sufficient to keep the antihydrogen cold, or whether some more active form of cooling[15] will be needed.

EXTRACTION OF ANTIMATTER FROM STORAGE

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 an electrostatically suspended 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, then directing them to the thrust chamber.[10]

It might be more desirable to form the antihydrogen as a cloud of charged microcrystals, each crystal a microgram in mass 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 preferentially extracted from the microcrystal cloud using electric fields, and directed down a vacuum line[30] 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 storage chamber vacuum.

CONCLUSION

Our major conclusion about antihydrogen propulsion is that the concept is physically feasible, but expensive. Yet, despite the high cost of antimatter, it may be a cost effective fuel in space where any fuel is expensive. There is very high risk in the development of antiproton annihilation 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. It is important to remember that many of the problems of capturing, cooling, slowing, trapping, and storing of (anti)protons and (anti)hydrogen can be done as low cost student thesis topics using normal protons and hydrogen.

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APPENDIX E

PRODUCTION OF HEAVY ANTINUCLEI: REVIEW OF EXPERIMENTAL RESULTS

PRODUCTION OF HEAVY ANTINUCLEI: REVIEW OF EXPERIMENTAL RESULTS

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PRODUCTION OF HEAVY ANTINUCLEI: SUMMARY OF EXPERIMENTAL RESULTS

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ABSTRACT

Antinuclei heavier than antiprotons, such as antideuterons, antitritons, antihelium-3, and larger antinuclei, might be useful in the initial phases of the nucleation and growth of antihydrogen cluster ions from antiprotons and antielectrons (positrons). The heavier antinuclei could possibly be used as seed catalysts to initiate the growth of a cluster ion, or to broaden or increase the number of infrared emission lines for radiation cooling purposes, or to break the symmetry of the smaller cluster ions, thus changing the large difference in binding energy between clusters with even versus odd numbers of atoms. There also may be other uses for heavy antinuclei, antiatoms and excited antiatom species that will be discovered once it is realized that small quantities can be obtained using variations on present antiproton production, capture, and trapping techniques. This paper summarizes the experimental work to date on the production of antideuterium, antitritium and antihelium nuclei, and the prospects for production of heavier antinuclei such as antilithium. The general experimental trend is that the ratio of production of antideuterons to antiprotons is 10^{-4}, antitritium and antihelium-3 to antiprotons is 10^{-8}, and each added baryon lowers the production rate by another factor of 10^{-4}. A typical facility using high energy protons striking metal targets can produce about 10^{15} antiprotons per day (about a nanogram), of which only 0.1% or 10^{12} (about a picogram) is captured. Thus, if special collection apparatus were used to separate out these heavier antiparticles and the collection efficiency was the same as that for antiprotons (0.1%), then along with the 10^{12} antiprotons being captured there would be 10^{8} antideuterons, 10^{4} antitritons and antihelium-3 nuclei, and 1 antihelium-4 nuclei. In addition, there are alternative proposals for producing antideuterium through colliding beams of antiprotons that may ultimately prove to be more effective in producing significant quantities of captured antideuterons. Extension of these techniques to colliding beams of heavy antinuclei may even allow fabrication of small amounts of very heavy antinuclei that are not feasible using the straight proton-target production approach.

INTRODUCTION

The availability of small numbers of heavy antinuclei may be useful in certain scientific and technological areas. Some examples would be the use of antideuterium and antitritium in the initial phases of antihydrogen cluster ion nucleation and growth, or the use of antihelium or antilithium with their multiple ionisation states as a catalyst for antihydrogen cluster ion or antihydrogen ice crystal growth. Muon catalysed fusion of antideuterium and antitritium to produce antihelium and an antineutron could also be attempted to search for any anomalous results from the use of antiparticles.

This paper is a brief review of the experimental results reported in the literature on the relative formation rates of heavy antinuclei. Most of this work was done in the 1970s, soon after the particle accelerator energies were sufficient to produce heavier antiparticles than antiprotons. After a brief flurry of papers, interest in production of heavy antinuclei dropped off and later papers only mention the production of heavy antinuclei in passing with the major emphasis being on searches for more exotic particles with approximately the same masses.

The threshold for production of antiprotons in pp collisions is 5.6 GeV, for antideuterons it is 15 GeV, for antitritium and antihelium-3 it is 28 GeV, for antihelium-4 it is 45 GeV, etc. For the efficient production of antinuclei it is necessary that the incident proton energy be considerably greater than these threshold values. For example, as the incident particle energy is increased from 30 to 70 GeV, the yield of antideuterons increases by more than an order of magnitude.

The production rate of heavy nuclei varies with a large number of parameters, the incident particle type and energy, the target type, and the output heavy antinuclei type, energy (momentum), and production angle. The variations with incident particle type, target nuclei type, and production angle turn out to be small (<50%). Even e^+e^- beam collisions give almost the same rates as proton-target interactions at the same center of mass energy. The major variation in production rate is the variation with output antiparticle type, with the antiproton production rate being a few percent of the pion production rate, the antideuteron production rate being 10^{-4} of the antiproton production rate, and succeeding antinuclei being down another factor of 10^{-4} for each additional antibaryon.

The simple model[1] that seems to fit the data is that it is necessary that several antinucleon-nucleon pairs be produced simultaneously, and that the antinucleons travel off in nearly the same direction at the same speed so they are close enough to "stick" together to form an antinucleus.

Most of the experimental measurements surveyed are reported as a ratio of the production of the heavy antinuclei at a given momentum and production angle compared to the number of negative pions with the same momentum and production angle, because this is an easy measurement to make. Sometimes this ratio is (or can be) converted to the number of heavy antinuclei at a given momentum and production angle compared to the number of antiprotons at the same momentum and production angle. Less seldom the absolute production rate of pions is also determined (or estimated) and an absolute production cross section for the heavy nuclei from the given target nucleus is given. There are small but significant differences in production rates from different target materials.

HEAVY ANTINUCLEI EXPERIMENTAL RESULTS

The first report of the production of antideuterons seems to have been in 1965 at the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory by a team from Columbia University[1]. They used the 30 Gev (BeV in 1960s notation) proton beam from the AGS on a beryllium target. About 200 heavy antinuclei events were reported and the ratio of antideuterons to negative pions at this low energy was only 5.5×10^{-8}. No firm evidence was found for antitritium. This team barely beat out another group in Europe[2] who also observed antideuterons using the 19.2 GeV/c proton beam from the CERN Proton Synchrotron. Their antideuteron to negative pion production ratio was 8×10^{-9}. In 1969 an IHEP-CERN Collaboration[3] made measurements at incident proton energies of 43, 52, and 70 GeV, and a number of antideuteron energies and production angles. This was followed in 1971 by further measurements at low antideuteron momenta by an IHEP team[4], again using 70 GeV protons on aluminum targets. The results of all the IHEP experimental measurements at 70 GeV is shown in Figure 1. At the peaks of the 70 GeV production curves, which occurred around 13 GeV/c secondary particle momentum, the ratio of antiprotons to pions was about 3×10^{-2}, and the ratio of antideuterons to pions was about 3×10^{-6}, giving a ratio of antideuterons to antiprotons of about 10^{-4}.

The same IHEP team[5,6] also reported in 1971 the first observation of antihelium-3 from 70 GeV protons on aluminum. A total of five antihelium-3 particles were observed out of 2.4×10^{11} particles (mostly negative pions) passing through the apparatus. The ratio of the differential cross section for the production of doubly ionized antihelium-3 nuclei at a momentum of 20 GeV/c compared to the negative pion at a momentum of 10 GeV/c was measured as 2×10^{-11} In 1974, essentially the same group[7] reported the production of four antitritium nuclei with 70 GeV protons on aluminum. The production ratio of antitritons to negative pions was about 10^{-11}. Although the statistics of the heavier nuclei are bad, it is possible to draw a trend curve of the relative production ratio. The (sparse) data for 70 GeV proton on aluminum production ratios of antideuterons, antitritons, and antihelium-3 nuclei with respect to antiprotons (instead of negative pions) is shown in Figure 2.

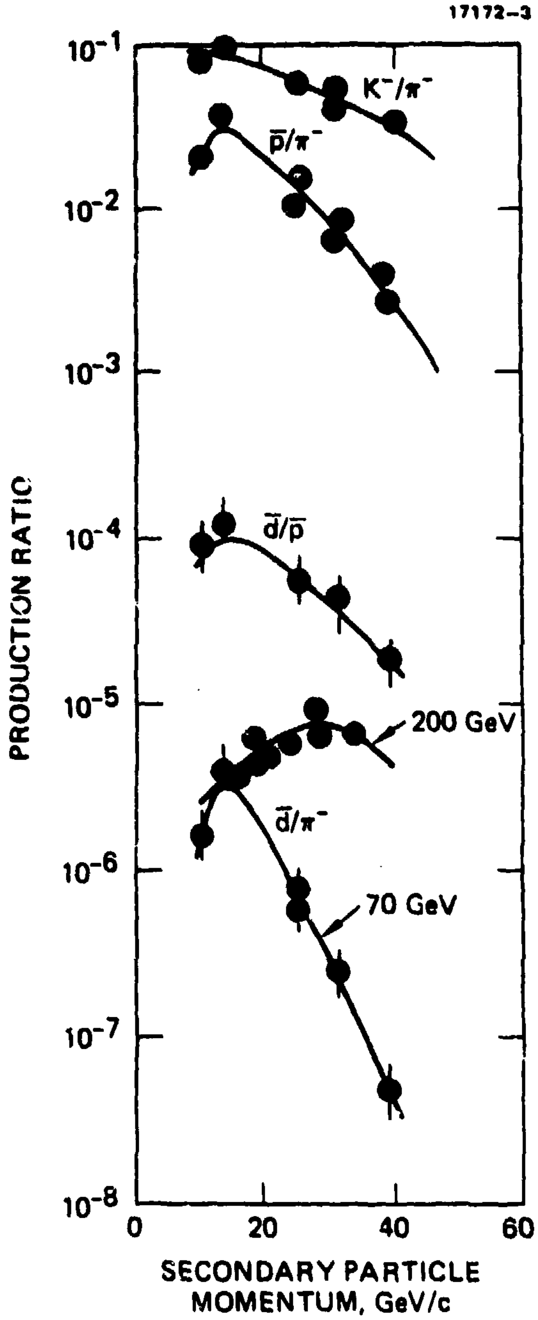

Figure E-1. Secondary particle production ratios as a function of secondary particle momentum for 70 GeV protons[3,4] and 200 GeV protons[8] on aluminum targets.

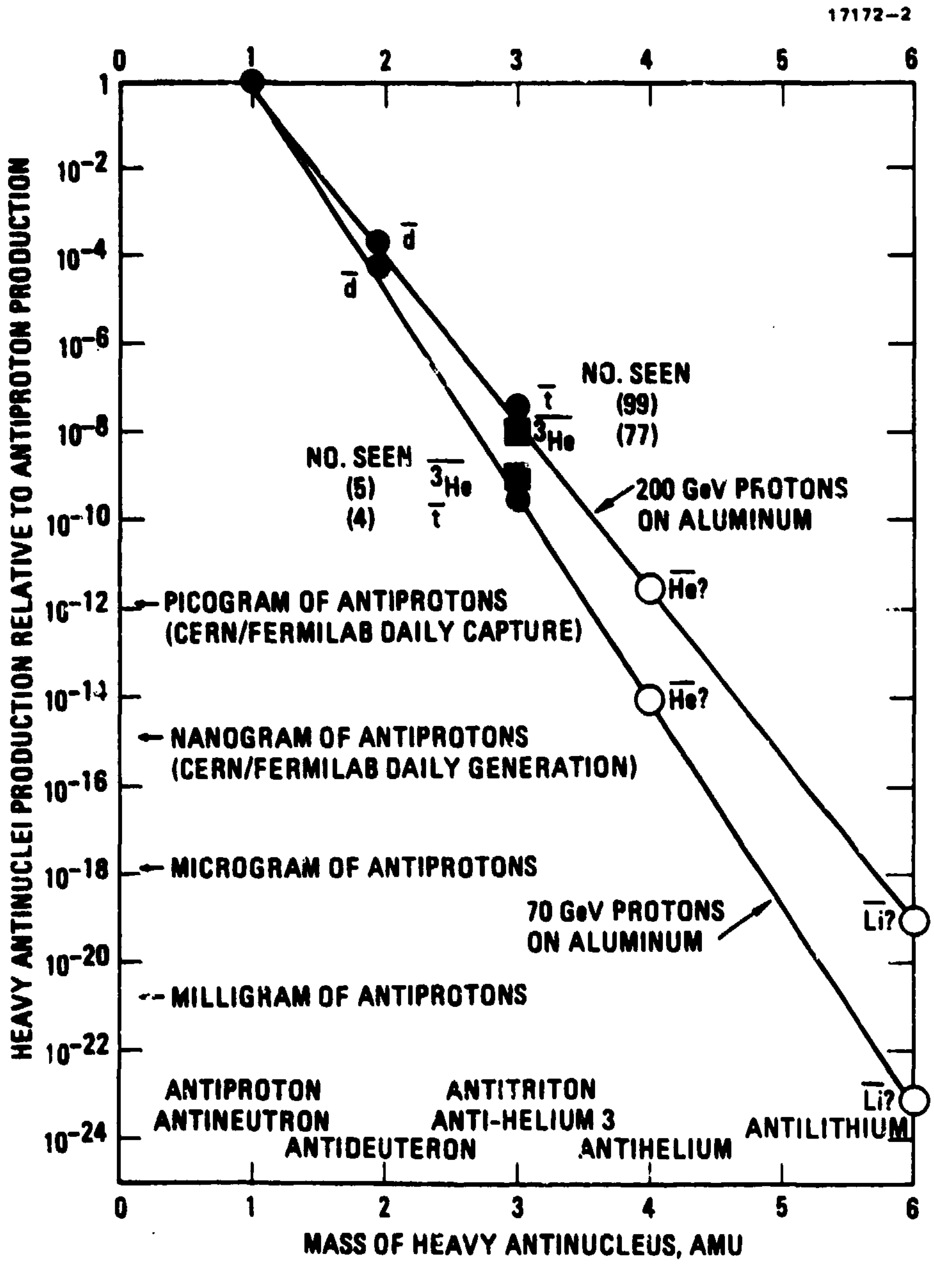

Figure E-2. Heavy antinuclei production ratio compared to the antiproton production ratio as a function of secondary antinucleus baryon number.

With the advent of the 200 GeV SPS machine at CERN, experiments were initiated in 1978 that produced copious quantities of antideuterons, ten antihelium-3 nuclei, and three antitritium nuclei[8]. The production ratio of antideuterons to negative pions was measured as a function of the secondary particle momentum and as shown in Figure 1, a broad peak was found at 30 GeV/c compared to the 13 GeV/c for antideuterons produced by 70 GeV protons. Later experiments[9] in 1979 increased the number of heavier antinuclei to 99 antitritons and 94 antihelium-3 nuclei. From this data the relative production ratio compared to negative pions is $3x10^{-2}$ for antiprotons, $4.6x10^{-6}$ for antideuterons, $1.3x10^{-9}$ for antitritium, and $3x10^{-10}$ for antihelium-3. This is also plotted in Figure 2 with the heavier antinuclei production ratios given as the production rate with respect to antiprotons rather than negative pions. At that time all the available data[1-12] on the production of antideuterons at low transverse momentum seemed to show a smooth trend as shown by the open data points in Figure 3 taken from Bozzoli, et al.[8] There was an increase in antideuteron production rate with increasing incident proton energy, leveling off at about $5x10^{-6}$ antideuterons per negative pion above 200 GeV. The solid line drawn through the data points is the square of the production ratio for antiprotons to negative pions at half the antideuteron momentum, as a simple model for the antideuteron production ratio.

Measurements in 1978 of the ratio of production of deuterons to antideuterons in proton-proton beam collisions at the CERN ISR Collider[12] at a center-of-mass energy of 53 GeV (1400 Gev equivalent p->N energy) gave a value of 3.8 deuterons to antideuterons, which is close to the square of the ratio of protons to antiprotons. This gives credence to the simple model[1] that if (anti)deuterons are produced as the result of the overlap of two produced (anti)nucleons, then the deuteron to antideuteron ratio should equal approximately the square of the ratio of protons to antiprotons at the same transverse momentum per (anti)nucleon.

Later experiments in 1985 that included correction factors for relative absorption of negative pions and antideuterons gave a value of $5.8x10^{-6}$ antideuterons per negative pion[13]. Then more data points were generated by other experiments with the highest energies being reached by experiments that involved protons colliding with protons. The data for the antideuteron to negative pion production ratio as a function of the equivalent incident beam momentum in many different experiments with different targets and different secondary momentum is shown as the filled spots in Figure 3 taken from Thron, et al.[13] The smooth trend with a leveling off above 200 GeV is now not so clear, and there could be a possibility that the production ratio of antideuterons (and presumably the heavier antinuclei) is increasing with increasing production energy above 200 GeV.

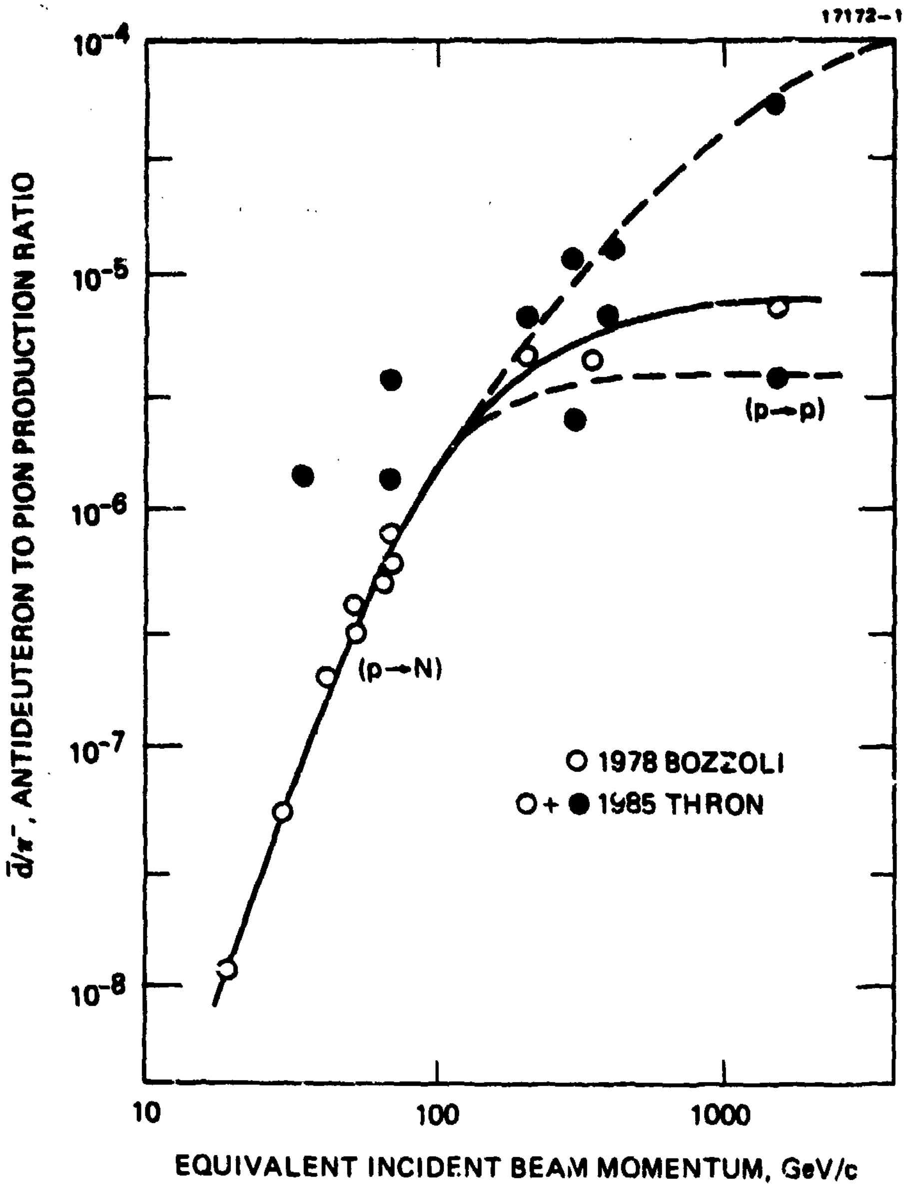

Figure E-3. Antideuteron to negative pion production ratio as a function of effective incident proton beam momentum.

Antideuterons have also been observed in electron-positron annihilation collisions at 10 GeV center-of-mass energy in the ARGUS detector at the DORIS II storage ring at DESY in Hamburg, Germany[14]. A total of six candidates passed the selection criteria for antideuterons. The production rate for antideuterons was about $2x10^{-5}$ per hadronic event compared to a production rate for antiprotons of $2x10^{-1}$ per hadronic event, or a ratio of antiprotons to antideuterons of 10^{-4}, similar to that observed in proton-proton or proton-target interactions.

PRODUCTION CROSS SECTIONS

A few production cross sections have been given in some of the papers. To convert production cross sections per target nucleus (usually ^{27}Al or ^{9}Be) to production cross sections per nucleon, the accepted procedure is to divide by $A^{2/3}$, which is 9 for Al and 4.33 for Be.

For 30 GeV/c protons on Be:[1]	
antideuterons at 5 GeV/c	$7x10^{-33}$ cm^2/sr•(GeV/c)•Be
For 70 GeV/c protons on Al:[4]	
antideuterons at 13 GeV/c	$3x10^{-36}$ cm^2/sr•(GeV/c)•Al
antitritons at 25 GeV/c	$1.0\pm0.6x10^{-35}$ cm^2/sr•(GeV/c)•Al
antihelium-3 at 20 GeV/c	$2.0x10^{-35}$ cm^2/sr•(GeV/c)•Al
For 200 GeV/c protons on Be:[9]	
antihelium-3 at 21 GeV/c	$1.3\pm0.3x10^{-34}$ cm^2/sr•(GeV/c)•Be
antihelium-3 at 47.4 GeV/c	$1.9\pm0.3x10^{-34}$ cm^2/sr•(GeV/c)•Be
antitritons at 23.7 GeV/c	$7.6\pm0.9x10^{-34}$ cm^2/sr•(GeV/c)•Be

SUMMARY OF EXPERIMENTAL RESULTS

If we extrapolate the data to date on the production of heavy antinuclei as shown in Figure 2, we can predict that at machine energies above 200 GeV, that for 10^{12} antiprotons captured (roughly one day's production at CERN or Fermilab) we could expect to capture 10^8 antideuterons, 10^5 antitritons, 10^4 antihelium-3 nuclei, and 1 antihelium-4 nuclei. Antilithium will have to wait for higher machine energies, greater beam currents, and especially better collection efficiencies.

Since machines exist that make large numbers of antiprotons using proton-target interactions, it is relatively simple to consider the installation of a diverter and a collection ring after the target and focusing lens to capture other particles than antiprotons. It might even be possible to make such an installation without significantly affecting the collection of antiprotons. It was estimated[15] in 1982 that the Antiproton Accumulator could store 2 antideuterons per production pulse at 3.5 GeV/c. At 7 GeV/c this number would be increased by a factor of 40. Another factor of 80 could be gained in the production rate if antideuteron beams of 30 GeV/c were produced from 200 GeV primary protons. Thus, for planning purposes, it is probably best to assume that if antideuterons or heavier antinuclei are urgently needed for some critical scientific experiments or to overcome some bottleneck in the development of antimatter technology, that they can be obtained using the same machiner that are presently producing antiprotons. There are alternate methods for producing heavy antinuclei, however, and they may have some advantages.

ALTERNATE HEAVY ANTINUCLEI PRODUCTION CONCEPTS

Since cooled antiproton beams are now available at low energy at CERN and high energy at Fermilab, it is possible to consider using these beams for the production of antideuterons through the reaction $\bar{p} + \bar{p} \rightarrow \bar{d} + \pi^-$. The process occurs in 8% of all $\bar{p}\bar{p}$ reactions. The details of arranging the reactions and capturing the resulting deuterons are discussed in two papers[15,16]. In principle the reaction could be iterated to produce antihelium ions and perhaps heavier antinuclei, although there have been no publications discussing this concept in any detail.

It is also well known that negative muons can be used as a catalyst to initiate fusion of a DT molecule to produce He^4 and an energetic fusion neutron. Once we have copious amounts of trapped neutral antihydrogen molecules with a large component of antitritium and antideuterium nuclei, we could attempt the formation of antihelium-4 by subjecting the trap to a positive muon beam.

ACKNOWLEDGMENTS

This research was supported by the Air Force Rocket Propulsion Laboratory through Contract F04611-86-C-0039.

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APPENDIX F

MIRROR MATTER NEWSLETTER
ISSUES 1 THROUGH 7

MIRROR MATTER Newsletter

This is a condensation of Issues 1-7 of the Mirror Matter Newsletter originally published June, July, August, October, and December 1986, and March and May 1987. The annotated bibliographies originally published at the end of each issue are now combined into one comprehensive bibliography.

The Mirror Matter Newsletter is a free, informal, aperiodically issued newsletter on the general topic of the scientific and engineering applications of stored antimatter. At present the community of interested people is spread out over a wide spectrum of disciplines, ranging from high energy physicists--to molecular spectroscopists--to rocket engine designers--to time and frequency specialists--to cluster ion experimentalists--to manned space enthusiasts.

Hopefully, this newsletter will let the different groups be aware of events and information they may not learn about through their normal formal and informal channels. The newsletter will be published only when there is a sufficient collection of interesting items to make it worthwhile. The present publication frequency is once every two months. The newsletter will cease publication when the normal scientific and engineering "gossip" channels typical to a field have established themselves.

News items, requests for back issues, additions and corrections to the mailing list, and requests for permission to reprint newsletter items should be sent to:

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MIRROR MATTER Newsletter
Vol. 1, No. 1, June 1986

MADISON ANTIMATTER WORKSHOP

Over 100 people attended the "Workshop on the Design of a Low Energy Antimatter Facility in the USA" held at the University of Wisconsin-Madison from 3-5 October 1985. The papers presented discussed antihydrogen physics, polarized antiproton sources, capture of antiprotons in traps, low energy antinuclear interactions, gravitational effects of antimatter, antiproton deceleration techniques, electron and stochastic cooling techniques, positron sources, positron cooling, and antihydrogen formation techniques.

Information about the Workshop Proceedings can be obtained from Cheryl Murray, (608)262-2281, Dept. of Physics, University of Wisconsin-Madison, 1150 University Avenue, Madison, WI 53706.

* * *

FERMILAB ANTIMATTER WORKSHOP

There were over 200 participants at the Fermilab Antimatter Physics At Low Energy (AMPLE) workshop held 10-12 April 1986 to discuss the desirability of a low energy antiproton facility at Fermilab. Presentations of interest were: D. Mohl, "Future Machine Improvements at LEAR"; P. Rapidis, "Fermilab Antiproton Source"; T. Goldman, "Gravitational Properties of Antimatter"; M. Hynes, "Physics with Bottled $\bar{p}$'s"; G. Gabrielse, "Prospects for Experiments with Trapped $\bar{p}$'s"; H. Poth, "$\bar{p}$ Atoms, Antihydrogen, and Hyperonic Atoms"; J.M. Richard, "$\bar{p}$-Nucleus Interactions"; and B. Deutch, "$\bar{p}$ Capture in Neutral Beams (How to Make Antihydrogen)".

Copies of the proceedings can be obtained from Phyllis Hale, Fermilab Users Office, P.O. Box 500, M.S. #103, Batavia, Illinois 60510, telephone (312)840-3111.

* * *

FIRST ATTEMPT TO TRAP AN ANTIPROTON

As this is being written, Prof. Gerald Gabrielse and a group of students from the University of Washington are at the Low Energy Antiproton Ring facility in CERN, Switzerland attempting to capture one or more antiprotons in a Penning trap (see review article on Penning traps by Brown and Gabrielse in the bibliography). The ultimate purpose of the experiment is to carry out a precision comparison of the inertial masses of an antiproton and a proton to a part in 10^9 or better (see proposal by Gabrielse, Kalinowsky, Kells, and Trainor in the bibliography).

The goal of the first set of experiments is to measure the energy straggling of antiprotons from 20 MeV down to 1 keV. The result may or may not be different than the energy straggling of protons in the same range, and could require changes in the thin film energy degrader at the entrance to the trap to make sure sufficient numbers of antiprotons emerge from the thin film into the trapping region.

The next step will be to shake out the procedural bugs in the capture technique and to attempt to capture one or more antiprotons. This attempt will most likely be made in a second run scheduled for July 1986.

Since the present trap and magnet are not of the high quality needed for a precise determination of the inertial mass, this work is preliminary to the final precise experiments, which will probably occur in late 1987 or early in 1988.

(The antiproton production and collection facility at CERN will be shut down from August 1986 to September 1987 for an upgrade that will hopefully increase the antiproton production rate by a factor of 10.)

* * *

MEASUREMENT OF ULTRAVACUUMS

If Prof. Gabrielse and his students are successful in trapping an antiproton and holding it for a long period of time, then in addition to everything else, they will have put an upper limit on the vacuum pressure inside a sealed cryogenic trap. It is guessed that the residual gas pressure in a sealed trap at 4.2 K is less than 10^{-22} Torr (10^{-6} atoms/cc). This pressure should be low enough for antimatter to be stored without significant loss. Present vacuum gauges cannot measure a pressure less than 10^{-14} Torr. Thus, these preliminary experiments will give us the first hard evidence that cryogenic vacuums are good enough to store antimatter for long periods of time.

* * *

AF ANNOUNCES INTEREST IN ANTIMATTER

In a television interview conducted by David Hartman of "Good Morning America" on 18 February 1986, General Lawrence A. Skantze, Head of the Air Force Systems Command, gave a brief summary of the results of the Project Forecast II study that he commissioned in the Fall of 1985. Of the 70 new concepts that survived the winnowing process of the Forecast II study and became major new technological thrusts for the Air Force, the trans-atmospheric vehicle and the use of antimatter for propulsion were specifically mentioned by Gen. Skantze.

* * *

AFOSR STARTS ANTIMATTER PROGRAM

The Air Force Office of Scientific Research has initiated a new program on antimatter research in the Physical and Geophysical Sciences Branch under Col. Hugo Weichel. The Program Manager for Antimatter is Maj. John Prince, at (202)767-4908.

As is standard procedure with AFOSR, unsolicited proposals for basic research may be submitted at any time. It is wise, however, to discuss your ideas with Maj. Prince before going to the trouble of preparing a formal written proposal. The mailing address is AFOSR/NP, Building 410, Bolling AFB, DC 20332-6448

* * *

PROJECT ARIES FORMED AT AFRPL

As a direct result of the Project Forecast II study conclusions, the Air Force Rocket Propulsion Laboratories at Edwards Air Force Base in California has reorganized its advanced propulsion activities and formed a new project called ARIES (Applied Research In Energy Storage).

The project has two thrusts, chemically bound excited states and antimatter. Those interested in working in these two fields should contact the project office.

It is planned that funding for the current fiscal year should come from reprogramming of funds already allocated to AFSC. The funding level is expected to grow in upcoming fiscal years.

The ARIES project leader is Dr. Robert C. Corley. He is assisted by Maj. Gerald D. Nordley, Dr. Steven Rodgers, and Capt. William Sowell. The project office telephone number is (805)275-5623 (AV525-5623), and the address is Project ARIES, AFRPL/CX, Stop 24, Edwards AFB, CA 93523-5000

* * *

$\bar{p}$-N ANNIHILATION STUDY COMPLETED

Dr. David L. Morgan of Lawrence Livermore National Laboratory has just completed a study report for the Air Force Rocket Propulsion Laboratory entitled "Annihilation of Antiprotons in Heavy Nuclei", AFRPL TR-86-011.

The objective of the study was to determine the fraction of the annihilation energy that becomes the kinetic energy of charged nuclear fragments emitted after the $\bar{p}$-N annihilation. The study was motivated by the fact that it is easier to couple the energy of charged nuclear fragments than the energy of the charged pions from a proton-antiproton annihilation, to a working fluid in a rocket.

The energy fraction was calculated to be about 10% for nuclei as heavy as silicon or heavier and 20% for very heavy nuclei when the energy of the fission fragments is included. If the non-interacting charged pion energies are included, the corresponding energy fractions are 30% and 40%.

All these values are less than or approximately equal to the fraction of annihilation energy (38%) that becomes kinetic energy in the charged pions from a proton-antiproton annihilation. These low values for $\bar{p}$-N annihilation occur because a significant amount of the annihilation energy goes into the kinetic energy of emitted neutrons.

Thus, for plasma combustion chambers of a few meters size, annihilation of antiprotons in heavy nuclei does not offer a significant advantage over annihilation of antiprotons with protons, if an effective means can be found to couple the kinetic energy of the charged pions into a working fluid.

Copies of the report may be obtained from AFRPL/LKC, Stop 24, Edwards AFB, CA 93523-5000

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ADVANCED SPACE PROPULSION STUDY

Dr. Robert L. Forward of Hughes Research Laboratories has been awarded a contract to carry out an Advanced Space Propulsion Study for the Air Force Rocket Propulsion Laboratory. The study, which will run from 1 May 1986 to 30 April 1987, will consist of a continuation of his prior studies into the critical research issues pertaining to antiproton annihilation propulsion, as well as an investigation into new concepts on the forefront of physics, chemistry, and engineering to discover new phenomena that might have application to space power and propulsion.

* * *

ENERGY LIMITED ROCKETS REVIEW PAPER

Antimatter rockets are fundamentally different in their operation from chemical rockets since (except for ultrarelativistic velocities) the energy source is separate from the reaction mass. A paper covering this topic, "Basic Considerations for Energy Limited Rockets", was recently completed by Gerald Nordley of AFRPL. In this paper, the equations governing the performance of rockets that use energy from a source external to the propellant are reviewed. A parametric set of equations governing the payload fraction of the initial mass of such a rocket is derived under the conditions of constant exhaust velocity and linear dependence of the tankage and energy storage masses on the propellant mass. The studies indicate that for energy-limited rocket systems carrying out high effective velocity missions (earth to low earth orbit, or round trip from low earth orbit to geostationary orbit) energy storage densities of the order of 1 GJ/kg will be needed. Preprints of the paper may be obtained from Maj. Gerald D. Nordley, AFRPL/CX, Edwards AFB, CA 93523-5000.

* * *

$\bar{p}$-H STUDY COMPLETED

Dr. David L. Morgan of Lawrence Livermore National Laboratory has completed his second study for the Air Force Rocket Propulsion Lab on the "combustion" processes taking place in a mass conversion or antimatter rocket. In antiproton annihilation propulsion, a possible choice for the annihilation process is to have low-energy antiprotons with a kinetic energy less than a few electron volts, annihilate with the proton nucleus of a hydrogen atom. At such energies an atomic rearrangement occurs in which the electron of the hydrogen atom is emitted, while the proton of the hydrogen atom and the antiproton form an excited bound state of protonium, which then rapidly annihilates.

In prior studies carried out in 1970 [D.L. Morgan, Jr. and V.W. Hughes, "Atomic Processes Involved in Matter-Antimatter Annihilation", Phys. Rev. **D2**, 1389 (1970)], it was found that the cross section for annihilation through this reaction at antiproton energies below 20 eV is much greater than that for annihilation of an antiproton on a bare proton. Similar high annihilation cross sections result when the antiproton is replaced by an antihydrogen atom. The prior study assumed that the Born-Oppenheimer approximation was valid. In the new study, a detailed investigation was made of the antiproton-hydrogen atom system when the Born-Oppenheimer approximation breaks down.

The new study found that the previous results were approximately correct, but there is a 20% probability for the rearrangement reversing prior to annihilation. This relatively small reduction in annihilation cross section is not significant for most antiproton annihilation propulsion system studies.

* * *

p̄ TRAPPING EXPERIMENTS PROCEEDING

It was mentioned in the June Mirror Matter Newsletter that the preliminary experiments on trapping of antiprotons were in progress at the Low Energy Antiproton Ring (LEAR) at CERN. The experiments are being carried out by a team consisting of G. Gabrielse, T.A. Trainor, S. Ralston, R. Tjoelker, Xiang Fei, and K. Helmerson from the University of Washington, H. Kalinowsky and J. Haas from the University of Mainz, and W. Kells from Fermilab. The team was successful in using a degrader foil to slow antiprotons from LEAR with kinetic energy of 21 MeV down to as low as 1 keV. Using a time-of-flight spectrometer, they then measured the energy distribution of the slowed antiprotons. They found that the energy distribution of the antiprotons was essentially the same as the energy distribution of the protons used to calibrate the degrader foil. Thus, the foil thickness in their present trap design will be suitable for their future experiments.

As a bonus, they were also able to briefly test the trapping apparatus they will use in July to try to capture the slowed antiprotons in flight. This was also a training period for the LEAR operator team, since most antiproton experiments ask for a very slow dump of the beam. For the antiproton trapping experiment, up to one-third of the antiprotons in the LEAR machine are to be dumped in as short a bunch as possible. The dump also has to be accurately timed with respect to the switching of the containment voltages in the Penning trap.

The team returns to CERN this month in an attempt to demonstrate the trapping of antiprotons. This antiproton trapping feasibility demonstration work is preliminary to the final precise experiments on a trapped antiproton planned in 1987. Those experiments will use a precision Penning trap to compare the inertial mass of an antiproton to the inertial mass of a proton to a part in 10^9 or better.

* * *

1985 SPRING MEETING OF APS

The 1985 Spring Meeting of the American Physical Society was held in Crystal City, Virginia from 24-27 April 1985. The abstracts of the papers are published in Bull. APS **30**, No. 4 (April 1985) at the page number indicated. To obtain reprints of the papers write directly to the authors. Some of the papers of interest are:

Arthur Ashkin, AT&T Bell Labs, "Trapping and Cooling of Neutral Atoms by Light", 669.

William D. Phillips, National Bureau of Standards, Gaithersburg, MD 20899, "Laser Cooling and Trapping of Neutral Atoms", 669.

Wolfgang Paul, University of Bonn, West Germany, "Electromagnetic Trapping of Neutral Particles", 700 [no abstract].

Richard J. Cook, Air Force Institute of Technology, "Quantum Theory of Confinement in a Rapidly Oscillating Field and Single-Atom Spectroscopy", 700.

J. Dalibard, Ecole Normal Superieure, Paris and W. Phillips, National Bureau of Standards, Gaithersburg, MD 20899, "Stability and Damping of Radiation Pressure Traps", 748.

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1986 SPRING MEETING OF APS

The Spring Meeting of the American Physical Society was held from 28 April to 1 May 1986 in Washington, DC. Abstracts of the papers were published in the Bull. APS **31**, No. 4 (April 1986) at the page number indicated. To obtain reprints it will be necessary to contact the authors directly. Only two papers were of interest to Mirror Matter Newsletter readers.

H.A. Schuessler and S. Chen, Texas A&M University, "Space Charge Effects in an Electrostatic Trap", 797.

J. Peoples, Fermilab, "Antiproton Sources", 827.

* * *

LAMPF II PLAN PRESENTED

At the Fall Meeting of the Division of Nuclear Physics of the American Physical Society, held at Nashville, Tennessee from 18-20 October 1984, H.A. Thiessen of the Los Alamos National Laboratory presented a plan for a 45 GeV 40 μA proton synchrotron called LAMPF II. The machine was compared in performance and cost with existing and proposed particle factories. The 45-GeV LAMPF II proposal was said to produce far more neutrinos, kaons, and antiprotons per unit cost than an upgraded conventional machine. The full abstract can be found in Bull. APS **29**, No. 7, 1069 (September 1984).

* * *

PARTICLE ACCELERATOR CONFERENCE

The 1985 Particle Accelerator Conference of the American Physical Society was held in Vancouver, British Columbia from 13-16 May 1985. The abstracts of the papers can be found in Bull. APS **30**, No. 5, (May 1985) at the page number indicated. Reprints of the papers have to be obtained by writing the authors directly. Some of the papers of interest are:

G. Dugan, Fermilab, "Tevatron I (Energy Saver and $\bar{p}$ Source)", 896.

C.D. Johnson, S. Maury, T.R. Sherwood, and A. Sullivan, CERN, "Injection into the New CERN Antiproton Collector Ring", 905.

T. Castellano, L. Bartoszek, E. Tilles, J. Petter, and J. McCarthy, Fermilab, "Kickers and Power Supplies for the Fermilab Tevatron I Antiproton Source", 905.

G. Dugan, M. Harrison, J. Dinkel, G. Krafczyk, M. May, and E. Tilles, Fermilab, "FNAL Main Ring to Energy Saver Antiproton Transfer System for Tevatron I", 905.

G. Dugan, et al., Fermilab, "Proton Extraction and Transport for Pbar Production in Tevatron I", 905.

Yu. Oganessian, Joint Institute for Nuclear Research, Dubna, USSR, "Heavy Ion Accelerator Development in the USSR", 932. [This was the only scheduled invited paper by a Russian. There is no abstract printed.]

S. Baird, LEAR Team, CERN, "Performance of LEAR", 932.

W. Kells, Fermilab, "Remote Antiproton Sources", 944-945.

V. Chohan, C.D. Johnson, and E.J.N. Wilson, CERN, "Antiproton Losses at Large Transverse Amplitudes in the CERN Antiproton Accumulator and Corrective Measures Using Skew Quadrupoles and Sextupoles", 951.

E. Brouzet, R. Cappi, J. Gonzales, W. Pirkl, and E. Schulte, CERN, "A Damper for the $\bar{p}$ Injection Oscillations in the PS Machine", 962.

W.C. Barry, LBL, "Suppression of Propagating TE Modes in the Fermilab Antiproton Source Stochastic Beam Cooling System", 984.

D.B. Cline and D. Larson, Univ. of Wisconsin; and F.T. Cole, F.E. Mills, and D. Young, Fermilab, "Intermediate Energy Electron Cooling of Antiprotons to Improve the Luminosity of Antiproton-Proton Colliders", 985.

C. Hojvat, et al., Fermilab, "FNAL Lithium Lens: Full Power Life Tests and Recent Design Improvements", 991.

R. Bellone and A. Ijspeert, CERN, "Development of Lithium Lenses at CERN", 999.

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ELECTRON & ATOMIC PHYSICS MEETING

The 16th Annual Meeting of the Division of Electron and Atomic Physics of the American Physical Society was held in Norman, Oklahoma from 29-31 May 1985. The abstracts of the papers presented were published in the Bull. APS 30, No. 5 (May 1985) at the page number indicated. Reprints of the papers presented should be obtained by writing the authors directly. Some papers of interest were:

H.F. Hess, MIT, "Magnetic Trapping and Cooling of Atomic Hydrogen", 854.

A.L. Migdall, W.D. Phillips, J.V. Prodan, NBS, Gaithersburg, MD and H. Metcalf and I. So, SUNY-Stony Brook, NY, "A Spherical Magnetic Quadrupole Trap for Laser Stopped Atoms", 856.

Chih-Ray Liu and Anthony F. Starace, Univ. of Nebraska-Lincoln, "Hydrogen Atom in a Strong Magnetic Field", 873.

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PROPULSION AREAS OF CONCERN

During a previous study on antiproton annihilation propulsion [R.L. Forward, "Antiproton Annihilation Propulsion", see bibliography], some technological areas were uncovered where there may be a "show stopper". If a major problem is uncovered in one of those areas, antiproton annihilation propulsion may not feasible. These areas of concern are listed below. If you have information relevant to those areas, please let me know.

Nucleation of Antihydrogen Matter:

Unless ways are found to store antiproton ions at high density, it will be necessary to convert the antiprotons into antihydrogen in a liquid or solid form and store that. The formation of antihydrogen liquid drops or ice crystals from a cold molecular gas produces heat from the latent heat of vaporization or fusion. To carry this heat away requires a third body. When condensing or freezing normal hydrogen, this third body is usually a dust particle or the wall of the experimental chamber. It may be found impossible to force supercooled antihydrogen gas to nucleate.

Papers by Seidel, Maris, and others [see bibliography] show that the absence of nucleation sites can have a significant effect on liquid to solid phase transitions. Whether this applies to nucleation from the vapor phase is unknown.

John Bahns of AFRPL has been looking into the nucleation and growth behavior of hydrogen ion clusters. He indicates that this may be a way to "work around" the nucleation problem.

Cooling of Antihydrogen Matter:

Antihydrogen ice must be kept below 2K to keep its vapor pressure low enough that the antihydrogen molecules sublimating from its surface do not heat up the storage chamber walls. Radiation cooling to the cold wall may not be adequate for handling heat leaks and no other technique works.

In a personal communication from Humphrey Maris of Brown University, calculations show that cooling a liquid drop below 4K by radiation takes a long time. John Bahns of AFRPL has indicated that hydrogen cluster ions may have a more emissive long wave infrared spectrum than solid hydrogen.

Antiproton Production Efficiencies:

The present techniques for generating antiprotons are extremely inefficient. It may be found impossible to build efficient proton accelerators, magnetic lenses, and accumulator rings to raise the overall energy efficiency from the present 10^{-5} to the desired 10^{-4} or better. At an efficiency of 10^{-4}, antiprotons would cost about 10M$/mg and antiproton annihilation propulsion is barely cost effective. At an efficiency of 10^{-5}, antiprotons would cost 100M$/mg and there would be only limited use for antiproton power and propulsion systems.

A major concern is the magnetic lens system. The present parabolic horns and cylindrical lithium lenses are being pushed to their limits. Does anyone know of a better lens concept?

Antimatter Rocket Design:

Antimatter rockets only give maximum benefits for space missions when the the rocket engines are operated at high thrust with exhaust velocities from 10 to 35 km/s (specific impulses from 1000 to 3500 sec). In a thermal rocket these specific impulses imply that the working fluid is a hot ionized gas. Yet to efficiently extract the kinetic energy from the annihilation pions the gas must be dense and therefore at high pressure. It may be impossible to design and construct a reaction chamber and rocket nozzle that can contain the pressures required and at the same time survive the heat and radiation.

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ANTIMATTER ROCKET STUDIES PLANNED

A study sponsored by the Air Force Rocket Propulsion Laboratory is currently underway at Los Alamos National Laboratory to develop an analytical baseline for the confinement of very high temperature rocket gases in magnetic chambers and nozzles. This effort will develop analytical models and computer codes that describe the flow field characteristics and transport properties of high density, low temperature plasmas. The plasma characteristics to be considered are those of high temperature hydrogen and helium type gases at pressures up to 1000 psi (68 atm) and temperatures up to 4 eV (46,400K). The results should allow evaluation of the effectiveness of the concept as a propulsion technique and give fundamental engineering parameters that can be used in the design of experiments and the future development of hardware. For information contact 2LT Ryan Haaland, AFRPL/LKCS, Edwards AFB, CA 93523-5000 [telephone (805)277-5640].

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ATOMIC-OPTICAL INTERACTIONS MEETING

A joint meeting of the Division of Atomic, Molecular, and Optical Physics and the Division of Chemical Physics of the American Physical Society was held from 18-20 June 1986 in Eugene, Oregon. Abstracts of the papers were published in the Bull. APS **31**, No. 5 (May 1986). To obtain reprints of the talks it will be necessary to contact the authors directly. Some interesting abstracts were:

S. Chu, Bell Labs, "Laser Cooling and Trapping of Atoms", 951. [Using counterpropagating laser beams along orthogonal axes, sodium atoms were stored for 1 s. Atomic velocities were 60 cm/s with a temperature of 2.4×10^{-4}K.]

J.E. Golub and T.W. Mossberg, Harvard Univ., "Unidirectional Acceleration of Atoms by Light Gratings", 957.

P.L. Gould, G.A. Ruff, P.J. Martin, and D.E. Pritchard, MIT, "Diffraction of Atoms by Light: The Near-Resonant Kapitza-Dirac Effect", 957.

P.L. Gould, G.A. Ruff, J.L. Picque, R.E. Stoner, P.J. Martin, and D.E. Pritchard, MIT, "Momentum Transfer to Atoms by Induced Processes in a Standing-Wave", 957.

M.W. Sealy and B. Van Zyl, Univ. of Denver, "Charge-Changing Cross Sections for H^+, H, and H^- Impact on H and H_2", 962.

A.L. Migdall, W.D. Phillips, and H.J. Metcalf, NBS-Gaithersburg, "Loading Optical Molasses with Atoms", 973.

G. Erez, T. Bergeman, and H. Metcalf, SUNY-Stony Brook, "Magnetostatic Trapping Fields for Neutral Atoms", 973.

R.S. Van Dyck, Jr., F.L. Moore, D.L. Farnham, P.B. Schwinberg, Univ. of Washington, "Multiply-Charged Ions in a Quadring Penning Trap", 973-974.

R.S. Van Dyck, Jr., et al, Univ. of Washington, "Single Proton Isolated and Resolved in a Penning Trap", 974.

E.E. Eyler, Yale University Physics Department, "Autoionization of Nonpenetrating Rydberg States Diatomic Molecules", 993.

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HEDG ANNUAL MEETING

The annual meeting of the High Energy Discussion Group was held at Brookhaven National Laboratory on 8-9 May 1986. This is an informal meeting and there are no proceedings, so reprints will have to be obtained directly from the authors. Papers of interest were:

D. Lowenstein, BNL, "BNL High Energy and Heavy Ion Facilities". Dr. Lowenstein reported that the heavy ion group expects to obtain 14.6 GeV per nucleon in fully stripped oxygen nuclei. He also reported that the AGS has obtained a duty cycle of 90% during normal operation.

B. Bonner, Rice Univ., "Polarized Proton Physics". The work to date on the use of polarized protons appears to offer little hope that incident particle orientation will affect the number of protons needed to produce an antiproton.

H. Poth, Karlsruhe, West Germany, "$\bar{p}$ Potential at the AGS". Dr. Poth described a project for producing a high luminosity, pure antiproton beam with the AGS machine at Brookhaven National Lab. [See preprint by Poth in bibliography and following item.]

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ANTIPROTON PHYSICS AT BROOKHAVEN

T. Kalogeropoulos and a collaboration from Austin, Bloomsburg, BNL, Case Western, CCNY, Houston, LeMoyne, LANL, Rice and Syracuse [see bibliography] have proposed to modify the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory to make it suitable for antiproton physics experiments in the range of 1 to 10 GeV/c. The AGS is presently being upgraded in proton intensity from $2x10^{13}$ to $5x10^{13}$ protons per pulse by the addition of a booster ring. The upgrade will be completed in 1989 and can serve many experiments with intensities only an order of magnitude less than those planned for LAMPF II.

What is now needed is a facility to collect and separate the antiprotons. Instead of building an accumulator ring, the proposal is to use a time-separated beam (TSB). Hugh Brown of Brookhaven has designed a 1 km TSB using available magnets. This beam transfers $2x10^{6}$ antiprotons per 10^{12} incident protons over a wide range of momenta (1%). The antiprotons get separated from pions by pion decay as well as time-of-flight in a bunched proton extraction mode.

The AGS Advisory Committee found the proposal to be interesting, but the cost was beyond BNL resources. A rough estimate of the beam and experimental area brought the price to about 10 M$. Several options have been considered which will reduce the cost to less than 5 M$. A working group meeting has been called for August by Don Lazarus (Head of Experimental Planning and Support at the AGS) to examine the various options and come up with an affordable cost.

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MIRROR MATTER Newsletter
Vol. 1, No. 3, August 1986

TRAPPING OF ANTIPROTONS SUCCESSFUL

The recent attempts to capture low energy antiprotons in a Penning trap at CERN have been successful. The experiments were carried out by a team consisting of G. Gabrielse, X. Fei, K. Helmerson, S. Rolston, R. Tjoelker, and T. Trainer of University of Washington, H. Kalinowsky and J. Haas of University of Mainz, and W. Kells of FNAL. Using a crude Penning trap with a thick foil degrader at the entrance, they slowed the 21 MeV antiprotons from the Low Energy Antiproton Ring (LEAR) machine more than four orders of magnitude down to 1 keV. The antiprotons were captured in flight by rapidly applying kilovolt potentials to previously grounded trap electrodes while the anti-protons passed through the trap. The spokesman, G. Gabrielse, reported that they repeatedly trapped as many as 200 antiprotons out of single 150 ns pulses of 10^9 antiprotons sent to the trap from LEAR. In a typical run, the antiprotons were held 100 s, then allowed to escape the trapping region to annihilate on a wall so the time-of-flight spectrum of the detected pions from the annihilation of the antiprotons could be measured.

The experiment was completed successfully despite the fact that they were working against time (they were given only 24 hours on the LEAR machine) and working against adversity (something went wrong with their trap and it had to be cycled up to room temperature just before their 24 hours was to commence). As a result, the trap temperature was not as low as they would have liked (~10 K), and the trap vacuum was coupled to the dewar vacuum, resulting in a trap pressure estimated at $\sim 10^{-6}$ Torr. Despite this, the observed holding times were greater than 100 s, in one case 10 minutes. These times are already long enough to permit holding the kilovolt antiprotons until the effect of the high intensity pulse has decayed away, then sending the trapped antiprotons into a high quality storage trap.

Further experiments will be done in late 1987 when the improved LEAR facility resumes operation. Those experiments will use a sealed vacuum, precision Penning trap to compare the inertial mass of an antiproton to the inertial mass of a proton to a part in 10^9 or better. Future experiments might include the direct measurement of the gravitational acceleration of an antiproton or the synthesis of antihydrogen. A paper presenting the results of the experiment has been submitted to Physical Review Letters. One important figure in the paper will show the number of antiproton annihilations detected as a function of the time the antiprotons were kept in the trap.

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$\bar{p}$ GRAVITY EXPERIMENT UNDERWAY

A recent paper presented by Ronald E. Brown [see bibliography] gives the present status of the proposed experiment to measure the gravitational acceleration of the antiproton. The technique consists in obtaining antiprotons of the lowest energy possible from the LEAR facility at CERN, decelerating them further in the external beam line, trapping and cooling them to ultralow energy, and measuring their gravitational acceleration by time of flight measurements.

The experiment (PS-200) has been granted CERN approval and presently consists of the following collaborators: R.M. Thaler of Case Western, M. Weiss of CERN, J.H. Billen, R.E. Brown, L.J. Campbell, K.R. Crandall, T. Goldman, D.B. Holtkamp, M.H. Holzscheiter, S.D. Howe, R.J. Hughes, M.V. Hynes, N. Jarmie, N.S.P. King, M.M. Nieto, A. Picklesimer, W. Saylor, E.R. Siciliano, J.E. Stovall, T.P. Wrangler of LANL, F.C. Witteborn of

NASA/Ames, B.E. Bonner of Rice, D.A. Church, D.J. Ernst, A.L. Ford, R.A. Kenefick, J. Reading of Texas A&M, V. Lagomarsino, G. Manuzio of Univ. di Genova, and N. Beverini, L. Bracci, and G. Torelli of Univ. di Pisa.

The team has constructed a test beam line at the Ion Beam Facility at LANL to begin developing the apparatus for the experiment. An H^- beam is obtained from an existing cw ion source and sent through a horizontal section, then turned into the vertical direction by a 90° magnet. The beam is steered and focused into a Penning trap situated in the 6 T field of a superconducting solenoid magnet. A chopping system will soon be installed to more nearly reproduce the LEAR beam characteristics.

The ongoing tests with this apparatus will allow them to study vacuum capability with a room-temperature ion trap, trap pulsing to capture protons or H^- ions, and the type of H^- source to be taken to LEAR. In a later phase they will test a variety of drift-tube designs to study the suppression of the work function patch effect, compression of the atomic lattice in the tube, and other criteria for use in the gravity experiment. In their initial tests they have run H^- beams of 5 to 20 keV energy and have obtained beam currents of 3 to 12 μA through the 3-mm diameter apertures of the tubes. They have obtained pressures in the trap region as low as 3×10^{-10} Torr, which should allow a sufficient captured-ion lifetime to demonstrate trapping.

The planned demonstration technique is to run the beam into the trap with enough voltage on the upper end cap of the trap to repel the beam, and then to pulse the lower cap to sufficient voltage to trap the ions. Several hundred milliseconds later the voltage on the upper cap will be dropped to release the trapped ions upward to be detected in a microchannel plate at the top of the short drift tube.

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TREATING CANCER WITH ANTIPROTONS

A research team led by Ted Kalogeropoulos of Syracuse University and Levi Gray of Bloomsburg State College in Pennsylvania, has shown that antiprotons can be used to destroy cancer cells with minimal effect on nearby healthy cells. Their calculations of the energy lost by antiprotons stopping in water shows that the radiation transferred is localized within 1 mm of the stopping point.

This "focusing" of the radiation is due to the heavily ionizing particles emitted from the nuclei where the annihilation takes place. Those charged pions and gammas from the neutral pions that don't interact with the nucleus, leave the body without depositing a significant amount of energy in the tissue. This new procedure could allow radiation treatment of small tumors in sensitive regions of the body such as the brain. [See two papers by Gray and Kalogeropoulos in the bibliography.]

Antiprotons can also provide detailed images of body tissue. When antiprotons annihilate with protons or neutrons in the nucleus of the atoms they release charged pions. Computerized tomography systems can detect these pions to produce radiographic images of the body's internal workings that are superior in quality to X-rays or CAT scans. The use of antiprotons exposes the body to minimal amounts of radiation.

To produce about one billion antiprotons--enough for one clinical application--would cost approximately $10 (provided one had a CERN or Fermilab handy). Because every hospital cannot afford such equipment, there is a need for a device that can carry antiprotons to treatment sites. To this end, Kalogeropoulos and the research team are developing a self-powered transportable "bottle" which will capture the antiprotons and contain them in a magnetic field trap for transport to where they are needed.

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COLLABORATORS WELCOME IN $\bar{p}$-N WORK

Nick DiGiacomo of CERN and LANL would like to bring to the attention of the readers of the MM Newsletter the recent work at CERN on the physics of antiproton-nucleus annihilation. Over the past few years a group consisting of K.D. Bol, M. Buenerd, J. Chauvin, M.R. Clover, R.M. DeVries, N.J. DiGiacomo, J.C. Dousse, J.S. Kapustinsky, D. Lebrun, P. Martin, P.L. McGaughey, G.R. Smith, W.E. Sondheim, J.W. Sunier, and Y. Yariv worked on an experiment (PS 187) at LEAR aimed at understanding low-energy antiproton annihilation in nuclei. Two recent publications describe the apparatus [see Sunier et al in bibliography], and the first physics results [see paper by McGaughey et al in bibliography]. There is also a preprint [see McGaughey et al in bibliography], soon to appear in Nuclear Instr. & Methods that should be of particular interest to people concerned with antiproton energy deposition in matter after annihilation. The methods used are applicable to a variety of applied problems.

The analysis of the experimental results are continuing, albeit at a rather slow pace as the group is also heavily involved in a large experiment at CERN using high energy heavy ion beams. They seem to find that significantly more charge is released in the form of light composite particles (deuterons and tritons) than would be predicted by intranuclear cascade and coalescence model calculations. These experimental results may have some impact on the conclusions reached by Morgan in prior theoretical studies discussed in MM Newsletter #1 and #2. Nick DiGiacomo states that the group would welcome collaborators in the further analysis of their LEAR experiment, particularly those interested in extending their methods to next generation experiments and applied problems. Contact Dr. N.J. DiGiacomo at CERN, CH-1211, Geneva 23, Switzerland.

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SDI POSITION ON ANTIMATTER RESEARCH

In response to a direct query by the editor of this newsletter, the Director of External Affairs of the Strategic Defense Initiative Organization, J. David Martin, wrote the following:

"The Defensive Technologies Study of 1983 (the "Fletcher Report"), which formed the technical basis of the Strategic Defense Initiative (SDI), investigated anti-proton beam weapons. The conclusion was that this area warranted further study. Later work by several laboratories showed that anti-matter physics could have a number of high-payoff benefits for national security, but that anti-proton beams did not appear to offer any advantages over neutral particle beams or to provide any specific strategic defense possibilities in the time frame of fundamental interest to the SDI (1995-2010).

"The SDI has continued to fund some basic physics analysis in this area and will continue to consider proposals. However, I doubt it will be a high-priority funding item until such time as fundamental containment and production questions have been experimentally addressed. I believe the priority placed on this by the Air Force will assure that this work is adequately funded.

"For further discussion, please feel free to contact Lt. Col. (Dr.) S. Peter Worden, who was responsible for investigating anti-matter physics during the Fletcher Study."

[LTC S. Peter Worden, SDIO, Washington, DC 20301-7100 USA.]

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MIRROR MATTER Newsletter
Vol. 1, No. 4, October 1986

AGS ANTIPROTON BEAM WORKSHOP

A workshop organized by Don Lazarus was held from 18-22 Aug 1986 at Brookhaven National Laboratory to examine affordable options at the Alternate Gradient Synchrotron for a hot antiproton beam facility in order to pursue physics at energies below 11 GeV/c. A group of sixteen physicists evaluated the following proposals: (1) to upgrade an existing beam; (2) to use the booster ring under construction as an antiproton storage ring; (3) to use existing transfer lines from the AGS to the CBA tunnel for a time separated and time purified beam; and (4) to re-evaluate the cost of a 1 km time separated/purified beam as originally proposed in AGS proposal E792 two years ago. An AGS internal report will become available soon which will summarize the results of the workshop.

The workshop participants were: T. Kalogeropoulous (Syracuse), C. Bonner (Rice), G. Mutchler (Rice), D. Peaslee (Maryland), L. Pinsky (Houston), H. Poth (Karlsruhe), K. Robinson (Case Western Reserve), D. Lee (LANL), and from Brookhaven: H. Brown, G. Bunce, A. Carroll, H. Foelsche, J.W. Glenn, D. Lowenstein, and A. Pendzick.

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ACCELERATOR APPLICATIONS CONFERENCE

The Ninth Conference on the Application of Accelerators in Research and Industry will be held at North Texas State University in Denton, Texas from 10-12 Nov 1986. The following abstracts may be of interest to the readers of the MM Newsletter. Abstracts may be read in Bull. APS **31**, No. 8 (Sept 1986) at the page number indicated. Copies of the papers must be obtained from the authors.

Nelson Jarmie, Los Alamos National Lab, p. 1275, "A Measurement of the Gravitational Acceleration of the Antiproton: An Experimental Overview". [Ed: Discusses experimental challenges: decelerating the antiproton beam with a radiofrequency quadrupole, trapping and cooling in electromagnetic Penning traps, launching and detecting the particles, obtaining extremely high vacuums, and high order electromagnetic shielding.]

R.A. Kenefick, Texas A&M Univ., p. 1275, "Considerations for Electromagnetic Antiproton Traps". (The selection of a Penning ion trap configuration as the capture, storage, and launching device for an experiment which will attempt to detect and quantitatively measure the gravitational acceleration of antiprotons is described. Techniques for cooling the trapped antiprotons from approximately 100 eV to near 4 K are discussed.)

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APS PLASMA PHYSICS MEETING

The 28th Annual Meeting of the Division of Plasma Physics of the American Physical Society will be held in Baltimore, Maryland, USA from 3-7 Nov 1986. Papers of interest to readers of the MM Newsletter follow. The abstracts can be read in Bull. APS, **31**, No. 9 (Oct 1986) at the page numbers indicated. Copies of the papers must be obtained from the authors.

F.J. Wysocki, W.S. Crane, M. Leventhal, A. Passner, and C.M. Surko, AT&T Bell Labs, Murray Hill, NJ 07974 USA, p. 1393, "Generation of an Anti-matter Plasma". (The construction of a single component anti-matter plasma device (AMP) is near completion. The AMP device, which is similar to single component electron plasma devices, uses an axial B field with electrostatic end plugs to trap slow positrons generated by a tungsten moderated ^{22}Na source. The expected confinement time is 5×10^3 s, which would give a total of 5×10^6 e^+, a central density of 9×10^6 e^+/cm^3, and a space potential of 35 V. The plasma temperature is expected to be 2 eV.)

D.L. Galbraith and T. Kammash, Univ. of Michigan, pp. 1410-1411, "Space Applications of the Magnetically Insulated Inertial Fusion Reactor". (The recently proposed magnetically insulated inertial confinement fusion approach is examined for possible utilization as a space-based power source or a propulsion scheme.) [Ed: Primarily a scheme for fusion propulsion, but the magnetic insulation concept may be useful for antimatter heated plasmas.]

T. Kammash and S. Swanekamp, University of Michigan, p. 1411, "Estimate of the Magnetic Field Generated in the Magnetically-Insulated Inertial Fusion Reactor". (One of the most important aspects of the magnetically insulated inertial confinement fusion is the generation of very large magnetic fields which serve to thermally insulate the hot plasma from the metallic shell. Although there has been experimental evidence of such fields, no analytical models exist that can predict them. We find that for reactor densities of $10^{21}/cm^3$ and temperature of 10 keV, magnetic fields of mega-teslas can arise.)

P. Chen, J.J. Su, and J.M. Dawson, Dept. of Physics, UCLA, p. 1465, "A Plasma Lens for High Energy Particle Beams". (It has been proposed that under certain conditions a slab of neutral plasma can act as a focusing lens for high energy particle beams.)

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CERN DOWN, FERMILAB UP

In August 1986, the antiproton production facility at CERN in Switzerland was closed down for modifications and improvements. The Antiproton Accumulator (AA) will be upgraded and when the AA comes back up again (expected in September 1987), it will have the Antiproton Collector (AC) working ahead of it. The AC will be designed to have twice the transverse acceptance of the AA in both planes and four times the momentum acceptance (6%). The AC will carry out a phase space "compression" of the incoming antiproton pulse using a combination of longitudinal and transverse stochastic beam cooling and bunch manipulation in phase space. This should increase the present antiproton production rate by an order of magnitude. In the meantime, the only source of slow antiprotons in the world, the Low Energy Antiproton Ring (LEAR) is also down. It will be undergoing upgrading and modifications for experiments to start in late 1987, including plans for trapping antiprotons in quantity.

In November 1986, the 8 GeV antiproton source at Fermi National Accelerator Lab will be commissioned. From November until March, Fermilab plans to use the antiprotons to tune up the collider operation in the Tevatron and do some physics with the BO collider detector.

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NO LEAF FOR FERMILAB

Each year a Physics Advisory Committee meets to evaluate the long range plans at Fermi National Accelerator Lab. This year the Committee considered the Low-Energy Antiproton Facility (LEAF) proposed by the recent Antimatter Physics At Low Energy (AMPLE) workshop held at Fermilab in April. The report of the committee is as follows:

"The Committee discussed briefly the physics opportunities available with a low-energy $\bar{p}$ facility. While a number of these opportunities are attractive, we note that such a facility already exists at CERN. While there may exist sufficient demand to warrant a second facility, the highest priority of Fermilab should be to aggressively pursue the unique programs of the Tevatron, including the proposed accelerator upgrades. We also note that one of the areas of low-energy $\bar{p}$ physics, the study of charmonium states, is already being addressed at Fermilab by E760. In summary, the Committee recommends that the Laboratory not pursue a low-energy antiproton facility unless a very compelling initiative is put forth by the interested experimenters."

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TELESPAZIO ANTIMATTER RESEARCH TEAM

A new group has been founded at Telespazio, Rome, Italy, to carry out research on antimatter propulsion. The Antimatter Research Team (ART) is coordinated by Giovanni

Vulpetti. They are interested in studies of antiproton and positron production and storage, antimatter engine simulation, and (in a number of years) something like a technology demonstration. The team would welcome any serious cooperation and exchange of ideas with other groups. They can be reached through Giovanni Vulpetti, Telespazio, SpA per le Comunicazioni Spaziali, Via A. Bergamini 50, 00159 Rome, Italy.

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RESEARCH ON HYDROGEN CLUSTER IONS

One of the critical problems identified in previous studies of the feasibility of using stored antihydrogen as an energy source was converting antiproton ions into antihydrogen ice. One approach is to use laser photons to assist in attachment of positrons to form antihydrogen atoms, the cooling of the atoms in a Lyman-α light trap to millikelvin temperatures, the combination of atoms to form antihydrogen molecules, cooling and trapping of the antihydrogen molecules (somehow) with other coherent ultraviolet photon sources, and then the combining of molecules to form macroscopic balls or crystals of antihydrogen ice. There has always been serious concern that this could even be done, much less done at reasonable production rates.

An alternate pathway has been identified by researchers at the University of Iowa and the Air Force Rocket Propulsion Laboratory. The approach involves the growth of condensed antihydrogen ice crystals directly from a starting antiproton ion through the mechanism of cluster ion formation. A cluster ion is a large collection of neutral atoms or molecules clustered around a (usually) single ion. The H_n^+ clusters can be quite large (n>1000). Since they are ionized, they can be kept in the same Penning trap containing the starting antiproton ions, avoiding the need for photon traps.

Analysis has shown that there is a threshold cluster ion size associated with each of the association pathways, after which growth proceeds with near unit probability. For n>29, H_2 molecules can be added without the association energy being great enough to disrupt or evaporate atoms or molecules from the cluster ion. For n>100, individual H atoms can be added with nearly 100% success.

It is expected that the larger cluster ions will have a rich infrared spectra that will allow for radiative cooling of their vibrational degrees of freedom that have been excited by the energy gained during the association process. Generally speaking, the larger the "seed" cluster ion, the fewer the problems with nucleation. Until these large "seed" ions have been produced, however, nucleation rates using this pathway will be prohibitively small. The bottleneck in the "containerless" nucleation process is in the stabilization of the small (n<29) cluster ions.

Thus, the problem presently under study is to determine the best way to get from the single antiproton ion state to the stable cluster ion (n>29) state. Although it may take many attempts, using exotic techniques, and high power special purpose lasers, to make the first antihydrogen cluster ion, once it has been formed it can be grown to large sizes, given multiple charges, then used as a "mother seed" to "bud" smaller cluster ion seeds for use in simpler bulk growth systems (if growing microgram crystals smaller than a grain of salt could be called "bulk" growth).

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HYDROGEN CLUSTER ION STUDY GROUP

The Hydrogen Cluster Ion Study Group (HCISG) was convened from 30 June to 11 July 1986 at the Laser Facility at the University of Iowa. The invited participants were William C. Stwalley, Kenneth M. Sando, and Dwight C. Tardy of the

University of Iowa and John T. Bahns of the University of Dayton Research Institute working at the Air Force Rocket Propulsion Laboratory. The purpose of the meeting was to analyze the problem associated with the "containerless" condensation of hydrogen cluster ions and to make recommendations for future research.

The HCISG concluded that the "cluster ion" technique is a reasonable approach to the problem of "containerless" nucleation of condensed hydrogen and recommended (among other things) that a workshop be held as a next step in the investigation.

Proceedings of the HCISG may be obtained from John T. Bahns, AFRPL/LKCS, Edwards AFB, California 93523-5000 USA, (805)277-5540. The proceedings contains the following papers:

J.T. Bahns, "The Cluster Ion Approach to the Condensation and Storage of Antihydrogen". (The problem of concentrating antiprotons and positrons into a high energy density form is analyzed from the viewpoint of the "containerless" condensation of cluster ions of hydrogen in ion traps using ion-neutral association. The constraints that lead to the proposed method and the available ion-neutral association channels are discussed. It is found that the condensation method should (if possible) avoid the use of neutral hydrogen dimers. It is concluded that the condensation to produce the first seed cluster ions need only be done once in order to surmount the problems associated with "containerless" condensation.) [Ed: Paper contains 68 references to publications on hydrogen ions.]

William C. Stwalley, "Analysis of 'Containerless' Condensation of Polyatomic Hydrogen Ions, with Emphasis on H_3^+ Association Channels".

K. Sando, "Small Molecule and Small Cluster Ion Formation in a Low-Density Containerless Mixture of Electrons, Protons, and Hydrogen Atoms."

J.T. Bahns and W.C. Stwalley, "Recommendations for a Workshop on the Cooling, Condensation, and Storage of Hydrogen Cluster Ions".

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CONTINUOUS MAGNETIC REFRIGERATORS

In order to keep solid antihydrogen for long periods of time, it is necessary to store it at temperatures well below that of liquid helium. At 4 K, the vapor pressure of hydrogen is only 2×10^{-7} Torr, and a crystal of antihydrogen won't last long at that temperature. The vapor pressure is dropping rapidly, however, and at 2 K the vapor pressure is 4×10^{-18} Torr, and at 1 K it is 8×10^{-39} Torr. Thus, if we can make and keep antihydrogen at temperatures well below 2 K, it should not evaporate away.

In order to prevent heating by radiation from the surroundings, the walls of any trap must be kept cold, preferably well below 1 K so that any heating is caused by other sources of energy. Such temperatures used to be very difficult to attain, requiring specially constructed He^3-He^4 dilution refrigerators or single cycle paramagnetic salt refrigerators.

Because of the interest in cooling infrared detectors and optics in space, however, continuously operating magnetic refrigerators have now been built (some space qualifiable) and will probably be available when needed for future research in the storage of antihydrogen.

The systems are relatively simple, consisting of a slowly rotating (8 rpm) wheel carrying blocks of paramagnetic crystals (such as gadolinium-gallium-garnet). The blocks of magnetic material first move into a high magnetic field region (usually supplied by a persistent current superconducting coil) where the magnetic material is magnetized and releases its heat into the high temperature bath at 4.2 K. The magnetic material continues rotating out of the magnetic field region to the cold loop heat exchanger where it demagnetizes and in the process cools off the load.

Typical weights of present models are less than 70 kg, efficiencies are 34% of the Carnot efficiency, and input powers of 15 W into the rotor can extract up to 1 W at 1.5 K. Use of different magnetic materials can allow even lower temperatures to be reached. Instead of using liquid helium evaporation to maintain the 4.2 K heat bath, a closed cycle refrigerator can be used to eject heat at room temperature. This completely closed, continuously operating system would require about 2 kW of input electrical power to obtain 0.5 W of cooling at 1 K.

Further information on these refrigerators can be obtained from Y. Hakuraku and H. Ogata, Mechanical Engineering Research Laboratory, Hitachi, Ltd., 502 Kandatsu, Tsuchiura, Ibaraki 300, Japan. A paper describing their refrigerator is scheduled for an early issue of the Journal of Applied Physics. [Ed: It was scheduled for 15 Oct 1986, but it didn't make it.] One of the U.S. developers of these magnetic refrigerators is Oscar Weinstein, Program Manager, Magnetic Refrigerator Development Program, Electro-Optical & Data Systems Group, Hughes Aircraft Company, P.O. Box 902, El Segundo, California 90245-0902 USA.

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NUCLEAR PHYSICS DIVISION MEETING

In collaboration with the Canadian Association of Physicists, the Annual Fall Meeting of the American Physical Society Division of Nuclear Physics was held from 9-11 Oct 1986 in Vancouver, Canada. A Workshop on Polarized Targets: New Techniques and New Physics, was held 7-8 Oct 1986 as part of the meeting. The following abstracts may be of interest to the readers of the MM Newsletter. Abstracts of the papers may be read in Bull. APS 31, No. 8 (Sept 1986) at the page number indicated. Copies of the papers will have to be obtained directly from the authors.

L.S. Pinsky, University of Houston, p. 1196, "Antiprotons and Polarized Targets". (Two promising concepts for polarizing antiprotons circulating in storage rings will be discussed. These are the so-called "spin-filter" and "spin-splitter" techniques. In either case an internal polarized pro on target is needed.).

Ronald E. Brown, Los Alamos National Lab, p. 1233, "Cold Antiprotons and Gravity", [Ed: Review of prior work by LANL.]

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MIRROR MATTER Newsletter
Vol. 1, No. 5, December 1986

CLUSTER ION WORKSHOP

The Cooling, Condensation, and Storage of Hydrogen Cluster Ions (CCSHCI) Workshop will be held at SRI International, Menlo Park, California, USA on 8-9 January 1986. The tentative agenda is:

THURSDAY 8 JANUARY 1986.

J. Bahns, "Introduction".

R. Forward, "Antimatter Propulsion/Hot to Cold Antiprotons".

R. Saxon, "Excited States of Hydrogen Clusters".

W. Stwalley, "Large Hydrogen Cluster Ions".

J. Weiner, "Formation of H_3^+ and H_2".

M. Bowers, "Small (n<11) H_n^+ Clusters".

H. Schaefer, III, "H_n^+ Radiative Properties".

W. Phillips, "Cooling H and H_2".

G. Gabrielse, "Trapping Antimatter".

D. Wineland, "Ion Traps".

D. Huestis, "Calculating Matter-Antimatter Annihilation Rates".

W. Lester, "(?)".

(R. Becker), "Cost of Laser Cooling".

(F. Rothwarf), "New Generation Permanent Magnets".

FRIDAY 9 JANUARY 1986

J. Bahns, "H Atom Formation and Key Problems".

H. Michels, "H_3^+ Topics".

H. Helm, "Relevant Processes in H_2".

K. Crofton, "The Work of T. Oka's Group".

L. Yoh, "The Work of Y. Lee's Group."

J. Mitchell, "The Dissociative Recombination of Electrons with Hydrogen Molecular and Cluster Ions".

T. McIlrath, "Long Duration Lyman-Alpha Sources for Atomic Hydrogen".

R. Lovelace, "Storage Rings for Neutral Atoms".

(J. Dimmock), "Future Prospects for Funding".

J. Bahns, "Open Forum and Closing Comments".

The papers presented at the workshop will be published in a Proceedings. Information about the workshop and copies of the proceedings can be obtained from: Dr. John T. Bahns, AFRPL/LKC, Edwards AFB, CA 93523-5000. Telephone (805)275-5540.

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NOVOSIBIRSK HIGH ENERGY ACCL. CONF.

The XIII International Conference on High Energy Accelerators was held at the Institute for Nuclear Physics (INP), Novosibirsk, USSR, from 7-11 August 1986. It is not known if there will be a published proceedings of the meeting. The following papers of interest to readers of the MM Newsletter were presented at the meeting. Copies of the papers must be obtained from the authors.

H. Edwards, Fermilab, P.O.box 500, Batavia, Illinois 60510 USA, "1985 Tevatron p̄p Collider Commissioning". (A report on the 1985 Tevatron p̄p Collider commissioning activities will be given. Goals for operation at Fermilab in 1986-87 and a possible future Tevatron upgrade program will be outlined.)

D. Johnson, S. Peggs, and A. Wrulich, SSC Central Design Group, Berkeley, California 94720 USA, "Proton-Antiproton Studies for the SSC". (The accelerator physics implications of a proton-antiproton alternative for the SSC main ring have been investigated for two different luminosities of $L=10^{32}$ and $10^{33}/cm^2$-s.)

V.V. Parkhomchuk, INP, Novosibirsk, 630090, USSR, "The Cooling of Heavy Particles". (Possibilities of electron and stochastic cooling from the antiproton stacking point of view are reviewed. The limitations of both methods are discussed.)

J. Marriner, Fermilab, P.O. Box 500, Batavia, Illinois 60510 USA, "Stochastic Cooling at FNAL" (The recently commissioned anti-proton source at FNAL contains 8 separate stochastic cooling systems. The Debuncher cooling systems are designed to cool the transverse beam emittance by a factor of 3 in 2 sec with a 2 GHz bandwidth. The stack tail system is designed to accept a flux of $3x10^7$ anti-protons per second with a 1 GHz bandwidth. The Accumulator core cooling systems are designed to provide a momentum spread of 0.1% and an emittance of 2π mm-mrad with a 2 GHz bandwidth.)

N.S. Dikansky, V.I. Kokoulin, N.Kh. Kot, V.I. Kudelainen, V.A. Lebedev, V.V. Parkhomchuk, A.N. Skrinsky, and B.N. Sukhina, INP, Novosibirsk, 630090, USSR, "Fast Electron Cooling for a Region of Small Relative Velocities". (The experimental results on the electron cooling of negative hydrogen ions (antiproton cooling simulation in the UNK program) are presented. For electron density $10^9/cm^3$ the cooling decrement of $5x10^{-10}/s$ was obtained.)

G.I. Silvestrov, INP, Novosibirsk, 630090, USSR, "Problems of Intense Secondary Particle Beams Production". (Discussed are the production problems of intense beams of secondary particles: positrons, antiprotons, π and K-mesons. Among these are the problems to collect the secondaries with a solid angle close to the production angle.

Considered are the parameters of large liquid lithium lenses used to collect the antiprotons in antiproton target stations.)

G. Dugan, Fermilab, P.O. Box 500, Batavia, Illinois 60510 USA, "Pbar Production and Collection at the FNAL Antiproton Source". (The implementation, commissioning, and future of the FNAL Antiproton Source is discussed. The system collects 8 GeV antiprotons produced by 120 GeV protons in a production target. The pbar flux is defined by the acceptance of the Debuncher ring, whose design is 20π mm-mrad in each transverse plane and ±2% in momentum.)

A.V. Yevtikhiyev, V.I. Kotov, V.P. Novikov, Yu.A. Romanov, M.A. Samarin, E.V. Serga, A.V. Kharlamov, Yu.S. Khodrev, IHEP, Serpukhov, USSR and B.F. Bayanov, T.A. Vsevolozhkaya, G.I. Silvestrov, INP, Novosibirsk, 630090 USSR, "Heat Processes in Targets at High Energy Proton Accelerators". (Problems related to radiation heating of secondary particles targets at high-intensity proton accelerators are treated. Heat processes in targets irradiated by 70 GeV proton beams having the intensity of 5×10^{13} ppp is described.)

L.R. Evans, CERN, CH-1211 Geneva 23, Switzerland, "p̄p in the SPS: Status and Development". (The SPS has now operated as a proton-antiproton collider for four long physics runs during which it has accumulated more than 1 inverse picobarn of integrated luminosity.)

R. Bellone, A. Ijspeert, P. Sievers, CERN, CH-1211 Geneva 23, Switzerland, "The Results of Prototype Tests and Transient Field Computations of the CERN Lithium Lens". (Successful life tests in the laboratory of the first two lithium lenses, pulsed at peak currents of 450 kA, are described.)

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PROJECT ARIES NEWSLETTER

The Applied Research in Energy Storage (ARIES) office at the Air Force Rocket Propulsion Laboratory (AFRPL) has started publication of an aperiodically published newsletter on the activities carried out on the project.

The AFRPL established the ARIES office in February 1986. The charter for the new office is to implement two of the Air Force Project Forecast II technologies, High Energy Density Matter and Antiproton Technology. Initial implementation plans had been developed by the Project Forecast II team and it is the task of the ARIES office to refine the plans, develop them further, and begin implementation of the technical efforts.

The AFRPL and the Air Force Office of Scientific Research (AFOSR) are jointly orchestrating the implementation of the antiproton technology program. Capt. William Sowell of the ARIES office is the focal point at the AFRPL and Maj. John Prince is the focal point at AFOSR. They will coordinate on planning, budgeting, proposal solicitation, proposal evaluation, and project management needed to develop this technology.

The current plan is to acquire expert, technical consultation from Rand Corporation under the auspices of Project Air Force at Rand. The next step in the implementation may be the selection of six to 10 nationally recognized experts to participate in a startup workshop. The output of the first workshop would be a tasking of the experts to review the technology issues, prepare plans to develop the technologies, write a report on their findings, and participate in a second workshop with a much larger number of attendees.

Both workshops would be planned and chaired by Rand Corporation in coordination with the AFRPL and the AFOSR. At the completion, Rand would compile all the papers and comments into one report. The end result of all this would be a firm research plan for the development of antiproton technology that would be followed by the AFRPL and the AFOSR in the outyears.

The AFRPL has made a firm commitment to implement Project Forecast II technologies. High Energy Density Matter is already moving at a fast pace with seven contracts issued. Implementation of Antiproton Technology is also proceeding, but at a slower pace. The funding level is lower and the technology issues are greater than in High Energy Density Matter.

It is Dr. Corley's intent to distribute the ARIES Newsletter to all of the people in government, industry, and academia involved in or interested in high energy density matter and antiproton technology. The purpose of the newsletter is to explain why AFRPL is working in these technology areas and to keep people informed about the current status of the ARIES project. The first issue of the newsletter contains a large amount of background data. Future issues will concentrate on the specific projects the ARIES office is managing.

Requests to be added to the mailing list for the ARIES Newsletter should be sent to: Dr. Robert C. Corley, Chief, ARIES Office, AFRPL/CX, Edwards AFB, CA 93523-5000. [Ed: Note new phone number prefix.] (805)275-5623 or AUTOVON 525-5623.

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MEETINGS YOU MIGHT HAVE MISSED

Three meetings concerning antiprotons were held this summer and your editor missed the announcements. It is not known whether there will be proceedings published. To find out, contact the organizers listed.

6TH TOPICAL WORKSHOP ON PROTON ANTIPROTON COLLIDER PHYSICS, Aachen Germany (30 June-4 July 1986), Karsten Eggert: RWTH-III Physikalisches Inst., Physikzentrum, Sommerfeldstr., D-5100 Aachen, Germany.

VII EUROPEAN SYMPOSIUM ON NUCLEON ANTINUCLEON INTERACTIONS: ANTIPROTON 86, Thessaloniki, Greece (1-5 September 1986), P. Pavlopoulos, CERN-EP, CH-1211 Geneva 23, Switzerland.

INTERNATIONAL SCHOOL OF LOW ENERGY ANTIPROTON PHYSICS. TESTS OF FUNDAMENTAL INTERACTIONS AND SYMMETRIES USING LOW ENERGY ANTIPROTONS, Erice, Italy (26 September-4 October 1986), R. Klapisch, CERN, CH-1211 Geneva 23, Switzerland.

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UPCOMING MEETINGS

The following meeting may be of interest to readers of the MM Newsletter. Please contact the organizer listed for further details and registration information.

LEAR WORKSHOP, Villars, Switzerland (4-14 June 1987), Catherine Leluc, EP Division, CERN, CH-1211 Geneva 23, Switzerland.

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POSITRON BEAM FACILITY MINIWORKSHOP

A small, informal workshop on the Design of a Positron Beam Facility was held on 11 December 1986 at the Idaho National Engineering Laboratory. The workshop followed a series of presentations on Positron Possibilities at the INEL on 10 December 1986. The speakers and the titles of their talks were:

E.H. Ottewitte, INEL, P.O. Box 1625, Idaho Falls, Idaho 83415 USA, "Overview of Possibilities for and with an Intense Positron Beam Facility at the INEL".

David B. Cline, Physics Dept., University of Wisconsin/Madison, Madison, Wisconsin 53706 USA, "Positron Needs for a B-Factory and Test Linear Collider".

Alex Weiss, University of Texas/Arlington, "Research at University of Texas/Arlington Center for Positron Studies; Future Possibilities with an Intense Positron Beam".

There will be no proceedings. Copies of presentations must be obtained from the speakers.

MIRROR MATTER Newsletter
Vol. 2, No. 6, March 1987

IT'S VOLUME 2 BUT NOT NUMBER 1

This is the sixth issue of a free, informal, aperiodically issued newsletter on the general topic of the scientific and technological applications of stored antimatter. The newsletter appears roughly every two months.

Librarians like the volume numbers on publications to coincide with the calendar, while the haphazard publishing schedule of the MM Newsletter makes the number of issues per year irregular. Therefore, for the convenience of all, the Editor has adapted the numbering convention of Nature, where the volume number coincides with the year, while the issue numbers are consecutive and do not start over with each new volume. Thus, this issue is Volume 2, No. 6, March 1987.

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L-5 SOCIETY OFFERS MAILING HELP

Because the MM Newsletter is distributed free, is educational in nature, and one of the possible future applications of antimatter technology is its use for rapid space travel, the L-5 Society, long known for promoting the development of space, has generously offered to assist in the printing and mailing of the Newsletter. The L-5 Society will shortly be merged with the National Space Society, who will continue this assistance.

It was hoped that this issue would be distributed by the L-5 staff, but we haven't yet found the software version of the Rosetta Stone that will allow our computers to talk to each other so the mailing list can be transferred.

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MM NEWSLETTER NOW HAS P.O. BOX

In anticipation of changes in the publication and distribution procedures of the MM Newsletter, a separate P.O. Box has been set up for correspondence with the editor.

Please notice the new address on the masthead and use it for all future correspondence including meeting announcements or other news items to be placed in the newsletter, additions or corrections to the mailing list, and requests for permission to reprint items from the Newsletter.

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PARTICLE PHYSICS PREPRINT SOURCE

This news is old to those in particle physics, but for those outside that community (like the editor) it is worth noting that many papers on antiprotons show up first as preprints, and there is an excellent source for information concerning those preprints. It is called Preprints in Particles and Fields (PPF) and it is issued weekly by the Library-Bin 82, Stanford Linear Accelerator Center (SLAC), P.O. Box 4349, Stanford, California 94305 USA.

PPF lists new high-energy physics preprints received during the past week at the SLAC Library. It also provides an "Anti-preprint" section which lists references to versions of the preprints that have recently reached print in scientific journals. As space permits, high-energy physics conferences are also announced.

Subscriptions to PPF normally run from 1 October to 30 September. Rate information is available from the Library. A surface mail subscription for US addresses is only $36. You will also want to order the PPF Address List and Workshop papers list (free with your subscription and a label with your address on it). The text of the PPF is also available from an on-line database using SPIRES, the Stanford Public Information and REtrieval System developed at Stanford University under National Science Foundation grants.

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PARTICLE ACCELERATOR CONFERENCE

The 1987 American Physical Society Particle Accelerator Conference will be held in Washington, D.C., USA from 16-19 March 1987. The following papers may be of interest to readers of the MM Newsletter. Abstracts of the papers were published in Bull. Am. Physical Soc., 32, No. 2, February 1987 at the page number indicated. Copies of the papers must be obtained directly from the authors:

P. Martin, J. Kinkel, R. Ducar, Q. Kerns, K. Meisner, H.W. Miller, J. Reid, S. Tawzer, and D. Wildman, Fermilab, "Antiproton Acceleration in the Fermilab Main Ring and Tevatron", p. 154. (Changes in the rf feedback system required for the acceleration of antiprotons are described. Data on acceleration and transfer efficiencies are presented.)

B. Autin, G. Carron, F. Caspers, S. Milner, L. Thorndahl, and S. van der Meer, CERN, "ACOL Stochastic Cooling System", p. 177. (Fast cooling is obtained using a 2 GHz bandwidth split into three equal sub-bands. Limitations due to weak input signals and high output power are overcome by using cryoelectronics and maintaining the electrodes close to the beam while the beam envelope is shrinking.)

V.K. Bharadwaj. J.E. Griffin, D.J. Harding, J.A. MacLachlan, Fermilab, "Beam Transfer from the Core of the Accumulator to the Main Ring in the Fermilab Antiproton Source", p. 187.

V.K. Bharadwaj. J.E. Griffin, D.J. Harding, J.A. MacLachlan, Fermilab, "Beam Transfer from the Debuncher to the Stacking Orbit of the Accumulator in the Fermilab Pbar Source", p. 187.

V.K. Bharadwaj. J.E. Griffin, J.A. MacLachlan, P.S. Martin, K.G. Meisner, and D. Wildman, Fermilab, "Operational Experience with Bunch Rotation Momentum Reduction in the Fermilab Antiproton Source", p. 190.

R.J. Pasquinelli, Fermilab, "Stacktail Momentum Cooling in the Fermilab Antiproton Source", p. 192-193.

William Kells, Fermilab, "Stochastic Cooling: Analyzing the Limits", p. 193. (Existing theories of stochastic cooling cannot be consistent. All treatments agree at low feedback gain. In the high gain limits, which are of interest in determining the practical limitations of the technique, filter cooling has been particularly poorly treated.)

LEAR Team, CERN, "Performance Update on LEAR", p. 202. (Indications will be given as to expected machine performance, and some of the fundamental limits in the ultralow momentum region of 60 MeV/c and below.)

F. Pedersen, G. Carron, V. Chohan, T.W. Eaton, C.D. Johnson, E. Jones, H. Koziol, M. Martini, S. Maury, C. Metzger, A. Poncet, L. Rinolfi, T.R. Sherwood, C.S. Taylor, L. Thorndahl, S. van der Meer, and E.J.N. Wilson, CERN, "Recent Machine Studies and Improvements of the CERN Antiproton Accumulator", p. 203.

C.D. Johnson, E. Jones, and T.R. Sherwood, CERN, "Antiproton Yield Expectations for the ACOL Project", p. 206. (An overall gain of at least 10 in antiproton yield is expected. The antiproton collector lens will be a lithium lens, but high-current magnetic horns and a plasma lens are also under development.) [Ed: The plasma lens concept is new and could be important if its internal absorption losses are low.]

B.J. Evans, R. Garoby, J. Jamsek, G. Nassibian, G. Roux, and J. Schipper, CERN, "The Antiprotons Production Beam for the CERN A.C.; Beam Experiments and RF Developments", p. 221.

J. Marriner, Fermilab, "Review of Physics, Technology, and Practice of Stochastic Beam Cooling", p. 226.

J.D. McCarthy, Fermilab, "Operational Experience with Tevatron I Antiproton Source", p. 226.

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HYDROGEN CLUSTER ION WORKSHOP HELD

The Cooling, Condensation, and Storage of Hydrogen Cluster Ions (COSHCI) Workshop was held at SRI International, Menlo Park, California USA on 8-9 January 1987, with an attendance of 40 people. The speakers and the titles of the papers were:

J. Bahns, "Introduction"

R. Forward, "Prospects for Antiproton Production and Propulsion"

R. Saxon, "Overview of Hydrogen Clusters"

W. Stwalley, "Large Hydrogen Cluster Ions"

J. Weiner, "Radiative Association in H_2 and Associative Ionization in H_2^+"

M. Bowers, "Small (n<11) H_n^+ Clusters"

H. Schaefer III, "H_n^+ Radiative Properties"

W. Phillips, "Laser Manipulation and Magnetic Trapping of Atomic Hydrogen"

G. Gabrielse, "Trapping Antimatter"

D. Wineland, "Ion Traps"

D. Huestis, "Calculating Matter-Antimatter Annihilation Rates"

R. Becker, "Implications of Laser Cooling Requirements for Antimatter Storage"

T. Kalogeropoulos, "Digital Applications of Antiprotons"

E. Ottewitte, "Potential Positron Beams via Fission Reactors"

J. Bahns, "H Atom Formation and Key Problems"

H. Michels, "Electronic Structure and Stability of Small Cation and Anion Hydrogen Clusters"

H. Helm, "Electronic Transitions in H_2"

W. Lester, "Quantum Monte Carlo Study of the MIES Associated with $H_2(X\Sigma_g^+)$ and $H_2(B\Sigma_u^+)$"

M. Crofton, "Infrared Spectroscopy of H_3^+)

L. Yeh, "Hydrogen Cluster Ion Spectroscopy Obtained Through Vibrational Predissociation"

J. Mitchell, "The Dissociative Recombination of Electrons with Hydrogen Molecular and Cluster Ions"

T. McIlrath, "Long Duration Lyman-Alpha Sources for Atomic Hydrogen Cooling"

R. Lovelace, "Storage Rings for Neutral Atoms"

J. Prince, "Future Prospects for Funding"

J. Bahns, "Closing Comments"

The papers presented at the workshop will be published in a proceedings. Copies of the proceedings will be free and can be ordered from Dr. John T. Bahns, AFRPL/LKC, Edwards AFB, CA 93523-5000 USA.

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PROJECT FORECAST II ON ANTIPROTONS

The Final Report of the Air Force Project Forecast II Study that was carried out in 1985-86 has now been published. The 10 page Executive Summary (replete with color art of advanced aerospace technology) contains the following statement:

"We are also enthusiastic about an admittedly high-risk search for ways to use antiprotons. These unusual particles, currently produced at several locations throughout the world, will, when combined with protons, release enormous amounts of energy--far greater than that produced from any other energy source. If antiprotons could be stored and then combined with protons in a safe manner, we would have an incredibly rich energy source available for propulsion and power."

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$\bar{p}$ SCIENCE AND TECHNOLOGY WORKSHOP

The United States Air Force has asked The RAND Corporation to help organize two Workshops to assist in devising sound approaches to the planning for and investments in future antiproton research projects. These workshops will include critical reviews of the current status of antiproton science and technology, and will evaluate a number of the complex scientific and technical issues involved if useful applications of macroscopic amounts of antiprotons are to be realized.

The first of these workshops is scheduled for 21-22 April 1987 at the RAND Corporation in Santa Monica, California, USA and will be largely devoted to detailed planning for a substantially larger four-day workshop sometime in August-September 1987. The topics to be covered in both workshops include: needs for near-term US low energy antiproton facilities; identification of those areas of basic science, technology, and engineering where a larger US community could become active in experiments involving artiprotons; the definition of critical experiments needed to answer questions about the physical feasibility of producing macroscopic amounts of antimatter; the uses of antiprotons and the reaction particles from annihilation as diagnostic probes for fundamental studies in condensed matter physics, biology, and medicine; the amounts of antiprotons needed for several levels of applications-related experiments; the uses of micro-releases of annihilation energy; and issues related to the scale-up of the current capabilities for production, collection, and storage of antiprotons.

There will also be discussion of a number of related special topics, such as portable storage traps; future prospects in accumulators and cooling; alternative paths to antihydrogen production, condensation, and storage; and possible system configurations for achieving adequate annual production amounts of antimatter in some form suitable for large scale applications. The long range (10 to 20 year) goals and objectives of the technology will receive substantial emphasis.

The desired output of the workshops will be a first version of a long-range program plan for the development of antiproton technology, thoroughly documented in a published set of papers and discussions.

Papers in the areas described above are invited. Travel expenses and an honorarium will be paid for those delivering an accepted paper. A limited number of these arrangements will be available for prospective participants from outside the USA, especially at the second workshop. The published proceedings may include some additional, commissioned, review papers on selected topics of special scientific and technological interest.

Those wishing to present a paper or obtain further information about the workshops should contact B.W. Augenstein, The RAND Corporation, 1700 Main Street, Santa Monica, California 90406 USA. Proposals for papers will be considered by an organizing committee which will include representatives of the Los Alamos National Laboratory, RAND Corporation, and other organizations.

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INTERNATIONAL LASER SCIENCE CONF.

The International Laser Science Conference was held in Seattle, Washington from 20-24 October 1986. This meeting was co-sponsored by the American Physical Society, and the Optical Society of America, and was the annual meeting of the APS Topical Group on Laser Science. The following papers may be of interest to readers of the MM Newsletter. The abstracts are published in the Bull. Am. Physical Soc., 32, No. 2 (February 1987) at the page number indicated. Copies of the papers will have to be obtained directly from the authors.

C. Cohen-Tannoudji, Ecole Normale Superieure et College de France, 24 rue Lhomond, F-75231, Paris CEDEX 05, France, "Theory of Atomic Motion in Laser Light", p. 281.

J.E. Bjorkholm, Steven Chu, A. Ashkin, and A. Cable, AT&T Bell Laboratories, Holmdel, NJ 07733 USA, "Experimental Observation of Laser Trapping of Atoms", p. 281.

P.L. Gould, A.L. Migdall, H.J. Metcalf, and W.D. Phillips, National Bureau of Standards, Electricity Division, Gaithersburg, MD 20899 USA, "Dipole Laser Trap for Neutral Atoms", p. 281.

D.E. Pritchard, C.E. Wieman, E.L. Raab, R.N. Watts, V. Bagnator, and R. Stoner, MIT, Cambridge, MA 02139 USA, "Light Traps Using Spontaneous Forces", p. 281.

A.L. Migdall, H.J. Metcalf, W.D. Phillips, and P.L. Gould, National Bureau of Standards, Electricity Division, Gaithersburg, MD 20899, USA, "Improved Collection Powers of an Optical Maxwell Demon", p. 281.

G. Gabrielse, X. Fei, K. Helmerson, S.L. Rolston, R. Tjoelker, T.A. Trainor, H. Kalowsky, J. Haas, W. Kells, obtain from G. Gabrielse, U. Washington, Seattle, WA 98195 USA, "First Capture of Antiprotons in a Penning Trap; a keV Source", p. 282. [Ed: see paper of same title in Phys. Rev. Lett. 57, 2504-2507 (17 November 1986).]

A. Ashkin, AT&T Bell Labs, Holmdel, NJ 07733 USA, "Laser Trapping of Rayleigh Particles by a Single-Beam Gradient Force Optical Trap", p. 290.

W. Kiefer, Karl-Franzens U. Graz, Institute for Experimental Physics, A-8010 Graz, Austria, "Raman-Mie Scattering from Optically Levitated Single Particles", p. 290.

Thomas R. Lettieri and Egon Marx, National Bureau of Standards, Gaithersburg, MD 20899 USA, "Resonance Light Scattering From a Suspension of Microspheres", pp. 290-291.

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POTENTIAL USES OF ANTIMATTER

Maj. Gerald Nordley of the ARIES Organization, CX, Air Force Rocket Propulsion Laboratory, Edwards AFB, California 93523-5000 USA has put together an interesting list on what experiments you can do with a given amount of antimatter. A condensed version follows:

<Attogram (ag=>$6x10^5$ $\bar{p}$=>180 μJ)
[Some research in progress]
  Inertial mass measurement
  Low velocity nuclear physics
Femtogram (fg=>$6x10^8$ $\bar{p}$=>180 mJ)
[Research in planning stage]
  Ultra-low vacuum measurement
  Non-destructive material analysis
  3D imaging of solid bodies
  Detection of interior flaws
Picogram (pg=>$6x10^{11}$ $\bar{p}$=>180 J)
[2-5 years, circa 10 M$]
  Gravitational mass experiment
  Treat inoperable tumors
  Cauterize inoperable lesions
  Anneal microfaults deep in solids
Nanogram (ng=>$6x10^{14}$ $\bar{p}$=>180 kJ)
[5-10 years, circa 50 M$]
  Long range interior analysis
  Small thruster tests 10 kW-18 s
Microgram (μg=>$6x10^{17}$ $\bar{p}$=>180 MJ)
[10-20 years, circa 100 M$]
  Med. thruster tests 1 MW-3 min
Milligram (mg=>$6x10^{20}$ $\bar{p}$=>180 GJ)
[20-50 years, ??? $]
  Large engine tests 300 MW-10 min
Gram (g=>$6x10^{23}$ $\bar{p}$=>180 TJ)
[??? years, ??? $]
  Large scale space transportation

I expect the list will grow and become less propulsion oriented as more people think about the possible applications of a compact, lightweight, energy source.

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MIRROR MATTER Newsletter
Vol. 2, No. 7 May 1987

DATE CHANGE FOR IV LEAR WORKSHOP

The IV LEAR Workshop will be held in Villars-sur-Ollon, Vaud, Switzerland from 6-13 September 1987 at the Palace Hotel (a Club Med Hotel). Previous meetings in this series have taken place in

Karlsruhe, Germany (1979), Erice, Italy (1982), and Tignes, France (1985).

The purpose of this Workshop is to discuss the physics from LEAR and other related topics. Results from the pre-ACOL phase will be reviewed, a discussion of experiments planned after the start of ACOL will be made, and their impact on our understanding of fundamental laws and interaction will be examined. Projects in Japan and the USA, as well as the future of LEAR in connection with other facilities will also be presented. In keeping with the spirit of the Workshop, participants are requested to stay for the whole duration of the meeting.

Following the tradition of the previous workshops, participation will be by invitation. However, given the facilities of the hotel, the conference organizers expect to be able to accept all of those interested in LEAR physics wishing to attend. A second (and last) announcement will be circulated mid-June 1987, containing a tentative scientific program as well as all the necessary travel information.

The scientific program comprises five main topics to which the following conveners have been assigned:

- MACHINE ASPECTS: P. [illegible]févre, D. Möhl, D. Simon.
- AntiN-N SCATTERING: F. Bradamante, P. Kroll, C. Leluc.
- AntiN-N ANNIHILATION, SPECTROSCOPY AND NONPERTABATIVE QCD: C. Amsler, L. Montanet, R. Petronzio, J.M. Richard.
- FUNDAMENTAL SYMMETRIES: Ph. Block, L. Tauscher.
- AntiN-NUCLEUS INTERACTION: G. Backenstoss, T. Ericson, [illegible] Ricci.

If you are interested in attending this Workshop, please contact the organizers immediately, as the deadline is already past. [The first announcement of this workshop was in MM Newsletter [illegible], No. 5, p. 5 (December 1986)].

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ATOMIC, MOLECULAR, OPTICAL MEETING

The 18th Annual Meeting of the Atomic, Molecular, and Optical Physics Division of the American Physical Society will be held in Cambridge, Massachusetts, USA on 18-20 May 1987. Papers of interest to readers of the MM Newsletter follow. The abstracts can be read in Bull. APS 32, No. 5 (May 1987) at the page numbers indicated. Copies of the papers must be obtained from the authors.

R.D. Knight, John Sohl, Yang Zhu, and Liang-Guo Wang, Ohio State University, "Field Ionization and Autoionization Studies of Rydberg States of Molecular Hydrogen", p. 1220. (Forced autoionization in very weak electric fields is observed.)

J.R. Ashburn, R.A. Cline, P.H.M. van der Burgt, W.B. Westerveld, and J.S. Risley, North Carolina State University-Raleigh, "Refinements and Results of the H(n=3) Density Matrix Experiment", p. 1221. (The n=3 density matrix of excited hydrogen atoms following charge transfer between protons and helium atoms is determined from the Balmer-α emission in electric fields.)

M.C. Brower and F.M. Pipkin, Harvard Univ., "Measurement of Partial Charge Exchange Cross sections for $H^+ + He \rightarrow He^+ + H(n=3)$", p. 1222.

J.H. McGuire, Physics Dept., Kansas State University, Manhattan, Kansas 66506 USA, "Scattering of Atoms with Electrons, Positrons, Protons, Antiprotons, and High Z Ions", p. 1222. (For single electron capture we predict that at high velocities, cross sections for capture by positrons are an order of magnitude larger than capture by protons at the same velocity.)

Sultana N. Nahar and J.M. Wadehra, Wayne State Univ., "Charge Transfer Processes During the Collisions of Positrons and Protons with Atomic Hydrogen", p. 1225. (The formation of positronium in different states by the impact of 20-500 eV positrons on atomic hydrogen are calculated.)

R.N. Watts, D.-H. Yang, B. Sheehy, and H. Metcalf, State Univ. New York, Stony Brook, "Deceleration and Cooling of a Thermal Beam of Rubidium", p. 1235. (We have used resonant radiation pressure from a pair of frequency swept diode lasers to decelerate and cool a thermal beam of Rb to zero velocity.)

A.G. Martin, V.S. Bagnator, G.P. Lafyatis, E.L. Raab, J. Landry, D.E. Pritchard, MIT, "Laser Cooling of an Atomic Beam in a Superconducting Magnet", p. 1235. (We have observed deceleration and velocity bunching of a thermal Na atomic beam. This slow atomic beam has been used to continuously charge a magnetic trap.)

G.P. Lafyatis, V.S. Bagnator, A.G. Martin, E.L. Raab, R. Ahmadbitar, D.E. Pritchard, MIT, "Continuous Slowing and Trapping of Na Atoms", p. 1235. (A decay time of trapped Na atoms of 2 min, due to collisions with the background gas, was obtained with samples of 10^8 atoms.)

E.L. Raab, A. Cable, M. Prentiss, D.E. Pritchard, S. Chu, AT&T Bell Labs, "Spontaneous Force Light Trap", p. 1235. (Trapping times greater than 10 minutes, densities greater than 10^8 atoms/cm^3, and temperature <1 mK.)

S.L. Gilbert, J.J. Bollinger, and L.R. Brewer, National Bureau of Standards, "Stored Ion Experiments Using a Cylindrical Penning Trap", p. 1235.

P.B. Schwinberg and R.S Van Dyck, Jr., Univ. of Washington, "Improved Penning Trap Defect Compensation", p. 1236.

P.L. Gould, P.D. Lett, and W.D. Phillips, National Bureau of Standards, Gaithersburg, Maryland, "Measurements of the Confining Power of Continuously Loaded 'Optical Molasses'", p. 1238. (Atomic densities of 10^8/cm^3 are confined to a volume of 0.2 cm^3 for 0.5 s.)

Dave Pritchard, MIT, "New Advances in Neutral Atom Trapping", p. 1241. [Ed: Invited review paper.]

H. Thorsheim, J. Weiner, University of Maryland, and P.S. Julienne, National Bureau of Standards, "Laser-Induced Photoassociation of Ultra-Cold Sodium Atoms", p. 1245. (Theory of a two-step process proceeding by a free-bound photon absorption by the colliding atoms to an excited molecular state followed by radiative stabilization.)

S.L. Rolston, G. Gabrielse, X. Fei, L. Haarsma, K. Helmerson, R. Tjoelker, T.A. Trainor, Univ. of Washington, H. Kalinowsky, J. Haas, Univ. of Mainz, and W. Kells, Fermilab, "Energy Distribution of Antiprotons Exiting a Thick Degrader", p. 1279.

F.J. Mulligan, St. Patrick's College, Maynooth, Ireland and M.S. Lubell, City College of CCNY, "A Design of a Hybrid Beam Transport with Brightness Enhancement Remoderation for Experiments with Slow Positrons", p. 1279.

M.H. Holzscheiter, Los Alamos National Lab, "Antihydrogen Formation in Electromagnetic Traps", p. 1279. (Formation rates can be enhanced by 10^5 when positronium atoms are used instead of positrons.)

G. Gabrielse, X. Fei, K. Helmerson, S.L. Rolston, R. Tjoelker, T.A. Trainor, University of Washington, Seattle, H. Kalinowsky, J. Haas, University of Mainz, Germany, and W. Kells, Fermi National Accelerator Lab, "First Capture of Antiprotons in an Ion Trap", p. 1280.

R.L. Brooks and J.L. Hunt, University of Guelph, "Helium Hydride at Cryogenic Temperatures", p. 1282. (The spectrum of HeH around 550 nm has been observed and analyzed for four isotopic combinations, tritium excepted.)

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WORKSHOP ON INTENSE POSITRON BEAMS

A Workshop on Intense Positron Beams will be held at Idaho National Engineering Laboratory (INEL) Research Center, Idaho Falls, Idaho, USA on 18-19 June 1987. The Workshop organizers are Eric H. Ottewitte of INEL and W.P. Kells of Fermi National Accelerator Lab.

The purpose of the Workshop will be to bring together all parties interested in the generation, handling, and uses of positrons. This includes positron beam users and makers from low energy to high energy physics. The Workshop will emphasize magnetic bottling and cooling, but not exclusively so. Positron users include HEP colliders, antimatter production, synchrotron and other light sources, positronium beams, polarized beams, positron microprobes and microscopes, traditional condensed matter physics, atomic and molecular physics, and materials science. The Workshop will attempt to quantify what is needed in intense positron beams and what intensities are feasible in the foreseeable future. For further information please contact:

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$\bar{p}$ ANNIHILATION IN NUCLEI STUDY

The study of the annihilation of antiprotons in nuclei (PS183) was begun in 1986 at the Low Energy Antiproton Ring (LEAR) at CERN by Gerald A. Smith of Pennsylvania State University and colleagues. A program for the continuation of this study, as well as the analysis and modeling of the data from PS183, has recently been selected for funding by the Air Force Office of Scientific Research.

The focus of the research is on the elementary particle and nuclear physics processes that take place when an antiproton annihilates in a heavy nucleus. These processes involve the ejection of numerous particles, including charged pions and kaons, gamma-rays, neutrons, protons, and heavier nuclear fragments, each of which carries some of the large amount of energy released in the annihilation.

An accurate knowledge of the amount of this energy, as well as its abundance among the various particles, could be important in the design of an antiproton annihilation engine for a future space vehicle. The study also calls for the modeling of energy transfer mechanisms to a propellant once the fundamental measurements have been completed.

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1st INT. LASER SCIENCE CONF.

The First International Laser Science Conference (ILS-I) was held in Dallas, Texas, USA in 1985. The Proceedings of the conference was published as Advances in Laser Science-I, William C. Stwalley and Marshall Lapp, Eds., American Institute of Physics Conference Proceedings No. 146, New York (1986). Papers of interest to the readers of the MM Newsletter are listed in the bibliography.

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2nd INT. LASER SCIENCE CONF.

The Second International Laser Science Conference (ILS-II) was held in Seattle, Washington, USA from 20-24 October 1986. It was the annual meeting of the American Physical Society Topical Group on Laser Science. Papers of interest were listed in MM Newsletter **2**, No. 6, 4-5 (March 1987). Many of these papers will appear in a proceedings to be published around June 1987, as **Advances in Laser Science-II**, American Institute of Physics, New York (1987).

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3rd INT. LASER SCIENCE CONF.

The Third international Laser Science Conference (ILS-III) will be held in Atlantic City, New Jersey, USA from 1-5 November 1987. The organizing committee consists of W.C. Stwalley, Chair, U. Iowa; M. Lapp, Vice-Chair, Sandia-Livermore; A.C. Tam, IBM-San Jose; J.L. Gole, Georgia Tech; R. Gross, Aerospace Corp.; and G.M. Iacono, Philips Lab. This meeting will include a session on "Laser Cooling and Trapping of Particles". A proceedings will be published in mid-1988 as Advances in Laser Sciences-III, by the American Institute of Physics, New York.

Those desiring more information about the meeting should contact:

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PRODUCTION OF HEAVY ANTINUCLEI

Small numbers of heavy antinuclei may be useful in certain scientific and technological areas. Some examples would be the use of antideuterium and antitritium in the initial phases of antihydrogen cluster ion nucleation, or the use of antihelium or antilithium with their multiple ionization states as a catalyst for antihydrogen cluster ion or antihydrogen ice crystal growth. Muon catalysed fusion of antideuterium and antitritium to produce antihelium and an antineutron could also be done to search for any differences in the behavior of matter and antimatter.

A literature survey of experiments for production of heavy antinuclei was recently completed [See Forward May 1987 in bibliography]. Most of the experiments were done in the 1970s. After a brief flurry of papers, interest in production of heavy antinuclei dropped off and later papers only mention the production of heavy antinuclei in passing.

By extrapolating the available data in the literature to date on the production of heavy antinuclei, it is predicted that at machine energies above 200 GeV, that for every 10^{12} antiprotons captured (roughly one day's production at CERN or Fermilab) we could expect to generate 10^{8} antideuterons, 10^{5} antitritons, 10^{4} antihelium-3 nuclei, and 1 antihelium-4 nuclei.

There also exist proposals for producing antideuterium using colliding beams of antiprotons. These techniques may ultimately be more effective in producing significant quantities of captured antideuterons than p+N production techniques. [See Möhl 1983 and Koch 1982 in bibliography.] The extension of these techniques to colliding beams of heavy antinuclei may even allow fabrication of small amounts of even heavier antinuclei, such as antilithium, that are not feasible to make using the straight high energy proton on target production technique.

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$\bar{p}$ SCIENCE AND TECHNOLOGY WORKSHOP

The First Antiproton Science and Technology Workshop was held at the RAND Corporation in Santa Monica, California USA on 21-22 April 1987. The Workshop was organized by Bruno Augenstein of RAND, and the participants included: R.A. Duffy from Draper Lab, Stephen J. Lukasik from Northrop Corporation, Keith A. Brueckner from UCSD, Theodore D. Kalogeropoulos from Syracuse Univ., Frank Scammell from DoD, S. Koonin from CalTech, Fred Mills, M. Gormley, and W. Kells from Fermilab, D.B. Cline from UCLA and Fermilab, Johndale C. Solem, L. Campbell, T. Goldman, and M.M. Nieto from Los Alamos National Lab, John Prince from AFOSR, Robert L. Forward from Hughes, David L. Morgan, Jr. from Lawrence Livermore Lab, W.C. Stwalley from Univ. of Iowa, B.E. Bonner from Rice University, J.T. Bahns, Gerald Nordley, William Sowell, Frank Mead, and Robert Corley from Air Force Astronautics Lab (AFAL-formerly AFRPL), Yolanda Jones from AFWL, James R. Powell, H. Takahashi, Derick Lowenstein, and Y.Y. Lee from Brookhaven National Lab, J. Mason from TRW, and Harris Mayer and Scott Pace from RAND

Corporation. Contents of the various sessions were:

BASIC SCIENCE AND TECHNOLOGY ASPECTS OF LOW ENERGY ANTIPROTONS.

- M.M. Nieto, "Fundamental Theoretical Background".
- Johndale Solem and H. Mayer, "Possible Antiparticle and Antimatter Technology Applications".
- T. Kalogeropoulos, "Science Applications Survey".
- W. Kells, "University of Washington Collaboration Basic Science Experiments with Trapped Antiprotons".
- B.E. Bonner, "CERN PS200 Collaboration Progress Report".

UNITED STATES LOW-ENERGY ANTIPRTON FACILITY OPTIONS.

- D. Morgan, "Low Energy Annihilation Phenomenology".
- F. Mills and M. Gormley, "FNAL Views on U.S. Low Energy Antiproton Facility Options".
- J. Powell, D. Lowenstein, and Y.Y. Lee, "BNL Views on U.S. Low Energy Antiproton Facility Options".
- T. Kalogeropoulos, "Extraction and Compact Storage of Antiprotons at 10 to 100 MeV".

ANTIPROTON STORAGE OPTIONS.

- W. Kells, "Ion Traps: Scaling Aspects and Formation of Antihydrogen".
- W. Stwalley, "Large Hydrogen Cluster Ions".
- J. Bahns, "Review of Hydrogen Cluster Ion Workshop".
- R.L. Forward, "Prospects for Obtaining Small Numbers of Heavy Antinuclei".
- L. Campbell, "Storage of Antiprotons in Microstructures in Normal Matter".
- T. Kalogeropoulos, "Antiprotons for Everybody".

SCALE-UP ISSUES AND PHYSICS CONSTRAINTS ON LARGE SCALE PRODUCTION OF ANTIPROTONS.

- L. Campbell, "Effects of the New High Temperature Superconductors".
- T. Goldman, "Proposed Advanced Hadron Facility: Applications to $\bar{p}$ Production".
- D. Cline and F. Mills, "Proposal for a Moving Target High Intensity Antiproton Source and a 4π Mirror Machine Antiproton dE/dx Collector".
- H. Takahashi, "$\bar{p}$ Production by Colliding Heavy Ion Beams".
- J. Powell, "Routes to Large Scale Low Cost Antimatter".

This first workshop was a planning session to prepare for a second and larger workshop that will be held later in 1987. At the completion of the second workshop there will be a proceedings published that will contain the papers given at both workshops plus a number of specially commissioned review papers. Information about the second workshop and copies of the proceedings can be obtained from:

Bruno W. Augenstein
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(213)393-0411 (x6520)

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APPENDIX G

ANTIMATTER SCIENCE AND TECHNOLOGY BIBLIOGRAPHY

1. PRODUCTION AND COLLECTION OF ANTIPROTONS
2. PRODUCTION OF HEAVY ANTINUCLEI
3. PRODUCTION OF LOW-ENERGY ANTIPROTONS
4. PRODUCTION OF ANTIHYDROGEN ATOMS, MOLECULES, AND CLUSTERS
5. SLOWING, COOLING, AND TRAPPING OF ATOMS, IONS, AND MOLECULES
6. LOW-ENERGY ANTIPROTON ANNIHILATION PROCESSES
7. NON-PROPULSION APPLICATIONS OF ANTIMATTER
8. ANTIMATTER PROPULSION
9. CONFERENCE PROCEEDINGS
10. ANTIMATTER NEWS AND POPULAR ARTICLES

1. PRODUCTION AND COLLECTION OF ANTIPROTONS

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7. NON-PROPULSION APPLICATIONS OF ANTIMATTER

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Appendix I. B.E. Bonner and L.S. Pinsky, "A Summary of Topics Discussed at the First Fermilab Antimatter Physics at Low Energy Workshop," pp. 455-462.

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A. Wolf, et al., "Status and Perspectives of the Electron Cooling Device Under Construction at CERN," p. 129.

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D. Gareta, et al., "PS-184: A Study of $\bar{p}$-Nucleus Interaction with a High Resolution Magnetic Spectrometer," p. 187.

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B.I. Deutch, A.S. Jensen, A. Miranda, and G.C. Oades, "p Capture in Neutral Beams," pp. 371-391.

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Lincoln Wolfenstein, "CP Violation and p̄p Experiments," pp. 227-241.

John F. Donoghue, "CP Violation Experiments Using Hyperons at a pp̄ Machine," pp. 242-250.

Carl B. Dover, "Physics with Polarized p̄'s," pp. 251-270.

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F. Myhrer, "Antiproton Annihilation and Quark Dynamic Selection Rules," pp. 285-292.

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W.R. Gibbs, "Creating High Energy Density in Nuclei with Energetic Antiparticles," pp. 355-369.

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G. Bassompierre, R.K. Bock, A. Buzzo, M. Dameri, T. Fearnley, J. Franz, M. Gazzaly, N. Hamann, T. Johansson, E. Khan-Aronsen, K. Kilian, J. Kirkby, K. Kirsebom, K. Kuroda, A. Kylling, F. Levrero, A. Lundby, M. Macri, M. Marinelli, L. Mattera, B. Mouellic, B.A. Nielsen, W. Oelert, Y. Onel, B. Osculati, G. Pauletta, M.G. Pia, M. Poulet, E. Rössle, A. Santroni, H. Schmitt, B. Stugu, S. Terreni, F. Tommasini, "JETSET: Physics at LEAR with an Internal Gas Jet Target and an Advanced General Purpose Detector," pp. 419-442.

Y. Onel and A. Penzo, "Spin Studies with a Polarized Jet Target in LEAR," pp. 443-454.

P. Lefevre, D. Mohl, D.J. Simon, "Future Machine Improvements in LEAR," pp. 69-82.

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Appendix I. B.E. Bonner and L.S. Pinsky, "A Summary of Topics Discussed at the First Fermilab Antimatter Physics at Low Energy Workshop," pp. 455-462.

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C.W. Clark, "Autodetaching States of Negative Ions," p. 379.

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Theodore E. Kalogeropoulos, "Antiproton Neutron Annihilations at Rest: The $\zeta(1480)$," p. 138.

John Peoples, Jr., "Prospects for $\bar{p}p$ Experiments in the TEV I Accumulator," p. 144.

V. Bharadwaj, et al., "A Proposal to Investigate the Formation of Charmonium States Using the PBAR Accumulator Ring," p. 166.

Carl B. Dover, "Low Energy $p\bar{p}$ Strong Interactions: Theoretical Perspective, p. 1.

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Michael H. Holzscheiter, "Trapping and Cooling of Externally injected antiprotons in a Penning Trap," p. 120.

C.F. Driscoll, "Containment of Single-Species Plasmas at Low Energies," p. 184.

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R.S. Conti and A. Rich, "The Status of High Intensity, Low Energy Positron Sources for Anti-hydrogen Production," p. 105.

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M. Sedlacek, "The Celsius-Ring in Uppsala: Electron Cooler Design," p. 196.

10. ANTIMATTER NEWS AND POPULAR ARTICLES

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