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Enabling Exploration of Deep Space: High Density Storage of Antimatter

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Summary

To answer many of the major questions in astrophysics, instrumented probes will have to be sent deeper into space, carry more instruments, and make faster trips-- in essence they must achieve much higher velocities than currently deliverable with today's technology. Missions to the Kuiper Belt, the heliopause, or the Oort cloud will require a revolutionary advance in propulsion to achieve their goals within reasonable time frames. In essence, future missions to deep space will require specific impulses between 50,000 and 200,000 seconds and specific masses of .1 to 1 kg/kw to be considered.

Antimatter has the highest specific energy of any source known to man. At nearly 10^{17} J/kg, it is three orders of magnitude larger than nuclear fission and fusion and ten orders of magnitude larger than chemical reactions. Currently, antiprotons are produced and stored in small quantities (10^8) in Penning Traps. Penning Traps are a mature technology but are limited in the particle density, thus the energy density, which they can contain. Antimatter must be stored in much higher densities to be applicable for missions into the outer realms of our solar system.

We have completed investigation of two main categories of antimatter in order to increase storage capacity of antimatter beyond that of Penning Traps: 1) reducing the annihilation at the walls of antiprotons stored as non-neutral plasmas in order to increase the storage capacity and 2) storing antihydrogen as a neutral gas to achieve higher storage densities. Our original concept in the first category investigated the possibility of imposing an external electric potential on carbon nanotubes or etched semiconductor tubes to increase the electron rigidity on the inside of the tube and, thus, suppress antiproton/ wall collisions. This concept was deemed impractical midway through the project. As a partial result of this effort, however, we did uncover a concept that may allow a non-neutral plasma to be contained in a Penning Trap like device with much greater capacity. In addition, we have formulated a method whereby the

capacity of a trap holding antihydrogen may be increased to levels necessary for low mass platforms on deep space missions.

The first method entails the use of an electromagnetic trap that is coated with either solid hydrogen or solid ammonia to reduce annihilation at the walls of the trap. The technique of using the ammonia layer relies on a theoretical phenomenon called Parelectricity to repel the approaching antiprotons from the walls of the container. The other concept relies on storage of antihydrogen. In a similar vein, if the concept of quantum reflection proves viable for antimatter, a coating of liquid helium may reduce the annihilation rate of the antihydrogen on the walls of the trap. Both of these concepts can be demonstrated with simple experiments. If these concepts are proven viable, then energy densities of several megajoules to gigajoules per kilogram may be stored in future devices. Such capacity will enable small research craft to be accelerated up to the velocities necessary to reach out to the Oort cloud and beyond.

Mission Requirements

In order to reach destinations of a few hundred astronomical units (AU) in a few decades, velocities of 100s to 1000s of km/s must be achieved. The kinetic energy of every kilogram of mass that acquires that velocity at the end of the propulsion phase will be significant. Table I shows some the missions currently being discussed by NASA as part of the planning of future space science programs. The Table also depicts the "characteristic" velocity that must be given to the platform to achieve the mission. This velocity may be equivalent to the average velocity for a mission in which the propulsion phase is the entire mission. The kinetic energy of each kilogram of mass is then shown. In order to produce these levels of kinetic energy, the potential-energy density of the entire ship will have to be greater than these levels at the beginning of the mission. Therefore, the energy density of the "fuel" will have to be substantially greater than these levels to account for the payload, structural, and engine masses. Energy densities of known sources are shown in Table II.

In addition, current estimates of specific mass and specific impulse for representative systems utilizing these sources are also shown. Comparing Table II and Table I, nuclear electric systems might be able to accomplish the 250 AU mission but not much further. The only systems that use on-board energy sources that can go into deep space are fusion or antimatter.

Table I
Velocities required for deep space missions

Mission	Velocity (km/s)	Energy Density (j/kg)
250 AU in 10 yrs	60	1.8e09
10,000 AU in 40 yrs	1200	7.2e11
α Centauri in 40 yrs	30,000	4.5e14

Table II
Energy Densities of Known Sources

Reaction	specific energy (j/kg)	specific mass (kg/kw)	specific impulse (s)
Chemical	1.5e07	?	470
Fission (100%)	7.1e13	35	5,000-10,000
Fusion (100%)	7.5e14	1	40k-60k
Antimatter	9.0e16	.01-.1	40k-100k

Typically, fusion systems are envisioned to be large, massive and complicated. Thus, the overall specific energy will be below the levels necessary for interstellar precursor missions. Alternatively, antimatter is considered to be expensive and difficult to produce. A recent[1] investigation by Schmidt et al., at the NASA Marshall Space Flight Center (MSFC) indicates that sufficient levels of production could be present within the next few decades. The issues of production and conversion into thrust are also currently being pursued by Synergistic Technologies under SBIR and STTR grants. At this point, the other major issue that is required to make future deep space missions possible is the need for high-density storage if the required specific energy levels are to be achieved.

Antiproton Storage- Status

Currently, antiprotons are produced at several high energy accelerator facilities around the world. One such facility in Europe, CERN, captures and decelerates the antiprotons down to energies where they can be injected into long term storage devices called Penning Traps[2]. Over the past tens years or so, great success has been achieved in collecting and holding antiprotons in Penning Traps. This technology now appears to be capable of storing antiprotons in densities up to 10^{11} per cm^3. With funding from the Jet Propulsion Laboratory, Dr. G. A. Smith and colleagues at Pennsylvania State University have built a portable Penning Trap that can contain 10^8 antiprotons. The 1/e storage time for the trap is about one week. A second generation trap[3], the High Performance Antimatter Trap (HiPAT), is under development at the NASA MSFC that has a design goal of holding 10^{12} antiprotons with a 1/e time of a few weeks (Figure 1).
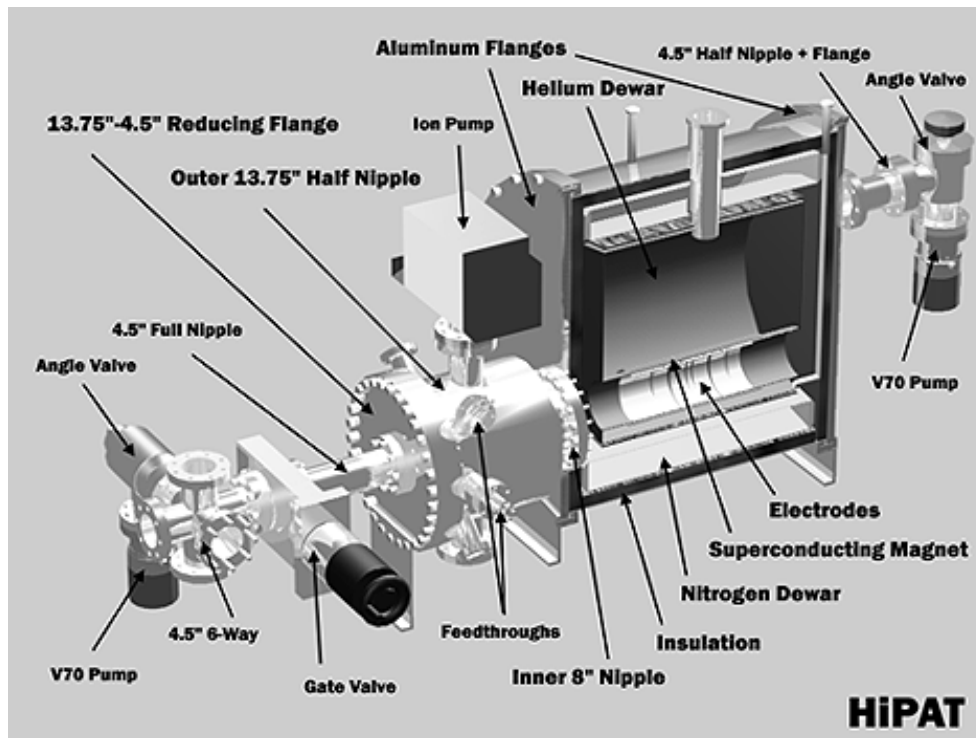

Figure 1 – Design of a high capacity antimatter trap (courtesy of NASA MSFC[3])

By using these traps as a source of low energy antiprotons, we intend to experimentally investigate other concepts that may store antimatter at densities 1000 times higher. We foresee in the next ten years great progress toward the confinement of antiprotons at much higher densities. This goal will be reached by a carefully planned and executed series of experiments.

High Capacity Storage of Antiprotons

Hydrogen reflection

The limiting factor in a non-neutral plasma such as that held in a Penning Trap is the Brillouin Limit. This is the density (about 100 billion antiprotons/cc for a 5T magnetic field) at which the stored space charge forces overcome the confining magnetic forces. Any truly significant steps beyond this limit would have to come from other physical phenomena. However, if a mechanism can be found that would reduce the losses of antiprotons as they hit the walls of the containers, then the capacity of traps could be increased substantially even though the Brillouin Limit is not exceeded.

One concept has been discussed in the literature by R.R. Zito[4], in which he advocates containment of a non-neutral plasma of antiprotons on magnetic field lines. The field lines also serve to generate a thin repulsive barrier of frozen solid hydrogen on the walls of a confinement vessel. Hence, antiprotons pushed outwardly by electric forces would be reflected back into the vessel's interior by collisions with the frozen hydrogen wall.

If the solid hydrogen atoms are maintained in a n=2, l=1 (P-state), m(l) =0 state, or a (2,1,0) state, then in the presence of a magnetic field the time-averaged density of the electron circulating around the proton appears as a two-lobed structure. The magnetic field, provided by a solenoid wound around the vessel, is required to separate the (2,1,0) state from the (2,1,1) and (2,1,-1) states. The total energy of the H-antiproton system in the (2,1,0) state is shown in Figure 2. A repulsive barrier, with a maximum at Ro = ao, where ao is the first Bohr radius = 0.53 Angstroms, is apparent. The total energy of the quantum state (2,1,0) is negative as shown, defining a range between about Ro and 3Ro over which repulsion occurs. In the absence of a magnetic field, all three quantum states exist, the charge density is spherical, and no repulsive forces exist.

When the hydrogen is in the ground state (1,0,0), it can be shown by similar arguments that the force on the antiproton is attractive. Hence, the need for a population inversion is clear. This would be done with the use of lasers. It is proposed to confine antiprotons in a container lined with frozen hydrogen in a population inversion and subject to a magnetic field of about 1 T. It is most important to note that the energy splitting between the (2,1,0) state and the (2,1,1) or (2,1,-1) state is only about

0.0001 eV. To prevent kinetic collisions from transferring the hydrogen into the m(l) = +-1 states, the atoms must have kinetic energy on average less than a temperature equivalent of 0.77 K.

In summary, Zito shows that antiprotons may be kept in a container lined with frozen hydrogen at less that 0.77 K temperature. The antiprotons will not annihilate as long as the lining is kept in a (2,1,0) population inversion in the presence of a modest magnetic field. The magnetic field also acts to confine the antiprotons within the interior of the container. The combination of inward radial magnetic confinement forces and repulsion from the vessel walls results in a stable radial configuration within the vessel. Electrostatically charged surfaces at the top and bottom of the container will provide axial confinement.
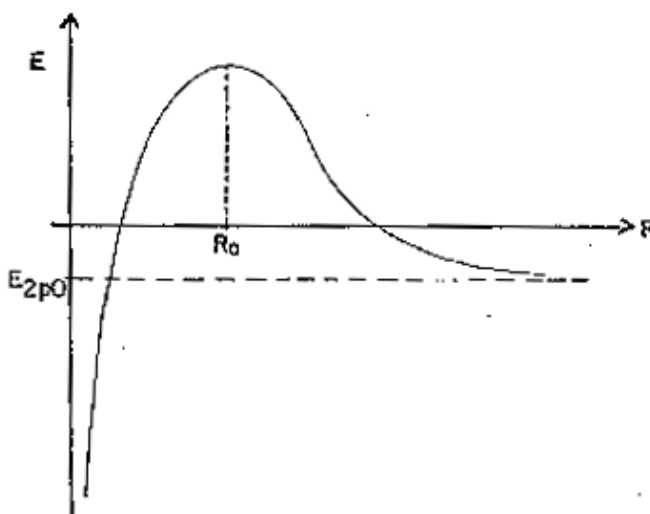

Figure 2-   Total Classical Energy of the H-antiproton System Plotted Versus the Proton-Antiproton Separation Distance R[4].

Parelectricity

In a similar methodology, recent publications by Chiao predict the possibility of a phenomenon called Parelectricity[5]. Parelectricity predicts that illumination of a layer of solid ammonia by 9.56 micron microwaves will create a population inversion in the material. One result of this inversion is that an image charge will be induced by an approaching charged particle that is of the same sign. Thus, the approaching particle will be repelled by the image charge. A thin layer of ammonia on the surfaces of the trap may reflect any approaching charged particle with near unity probability. Therefore, the original idea of making the walls of the trap reflective is still valid — just the methodology has changed.

Synergistic Technologies

It appears rather straightforward to experimentally check the validity of these considerations. Cool antiprotons could be injected from the MSFC HiPAT presently under construction, or the Penn State/JPL Mark I trap, into a container which is laser cooled to a temperature below 0.77 K for the hydrogen reflection concept. Similarly, the cavity can be illuminated with a microwave source to confirm Parelectricity. Measurements of reflection coefficients on the walls, and overall lifetimes of antiprotons, could be done fairly simply once the containment vessel is built, "iced", and magnetically or laser excited.

High Capacity Storage of Antimatter

Antihydrogen

We have examined another very promising advanced technology, i.e. synthesis and storage of atomic antihydrogen in Ioffe-Pritchard traps, which is capable of achieving very high density storage (10^{14}-10^{17}/cc). This technology is currently being developed at the Antiproton Decelerator facility at CERN, in Geneva, Switzerland, by the ATHENA experiment[6], of which one of us (G.A. Smith) is a collaborating member.

The major advantage of this technique is that one is working with electrically neutral atoms, so all space charge problems are eliminated. Furthermore, the magnetic properties of the atoms make them controllable under the influence of external electromagnetic fields. In the ATHENA trap antiprotons and positrons (antielectrons) are made to cohabitate a common volume using nested double-well potential barriers, as seen in Figure 3.

The ATHENA experiment at CERN will attempt to synthesize atomic antihydrogen next year. Very dilute mixtures of antiprotons and positrons (10^7 each) will be synthesized into antihydrogen atoms at 4K and below by spontaneous radiative recombination at densities of roughly 10^7/cc. Since the rate for spontaneous radiative recombination scales as $1/T^{.5}$, every attempt will be made to achieve sub-K temperatures in this experiment. Nonetheless, at about 1K, the expected recombination rate is 9,000 per second. The atoms are to be confined in an Ioffe-Pritchard trap which in the case of hydrogen has confinement densities approaching 1 microgram/cc for minutes.

Once formed, the antiatoms are confined in an Ioffe-Pritchard trap, a technology which has been used successfully for many years to confine hydrogen atoms at high densities for fundamental physics measurements. A gradient magnetic field is provided by current-carrying quadrupole coils. A force due to the gradient magnetic field is imposed on the magnetic moment of the atom.
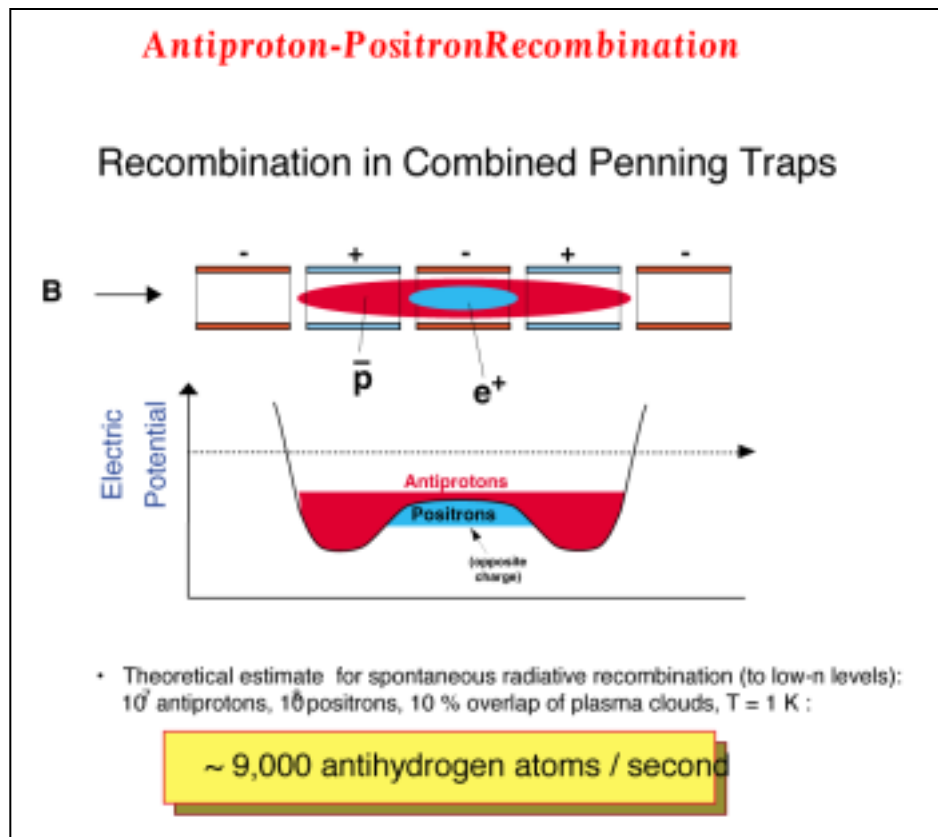
Figure 3– Antiproton-Positron Recombination (courtesy ATHENA, CERN)

Since the moment results from the combined spins of the constituents, and these in turn follow the rules of quantum mechanics, there are four hyperfine spin states possible. The low field seeking state, with the positron and antiproton spins parallel and pointing up, feels an attractive force into the center of the trap, and is confined. The state with the positron and antiproton spins antiparallel (high field seeking) is expelled from the trap.

Once confined in sufficient numbers, 243 nm wavelength lasers excite the antiatom from its 1S ground state to the 2S excited state. This state is metastable, with a lifetime of 1/8 second. An externally applied electric field mixes the 2S state into the 2P state, which can quickly decay by Lyman alpha photon emission back to the 1S state. This exercise demonstrates the existence, and numbers, of antiatoms in the trap, and leads to continued cooling of the antiatoms. The purpose of the ATHENA experiment is to do precision spectroscopy measurements of the antiatom; the technologies which they employ may show us the way to high density storage of such antiatoms.

By spontaneous radiative recombination, the particles bind to form an antihydrogen atom, which has all the properties of the hydrogen atom apart from the opposite charges of the constituents. The recombination rate is estimated by ATHENA at 9,000 per second at a temperature of 1 K. Since the recombination rate scales as $(1/T)^{.5}$ the rate could be increased one thousand-fold by laser cooling the atoms, for example, to a temperature of 10^{-6} K. At this rate, one could form 10^{14} antiatoms in about 10^7 seconds, or 4 months.

As with all electromagnetically-confined systems, ultimately regions of instability are found. In the case of the Ioffe-Pritchard traps, when confined atomic densities increase, interatomic scattering becomes important, resulting in electron (positron) spin flips, taking the atom from a low field seeking state to a high field seeking state. The newly created high field seeker then jumps out of the trap, lost forever. At densities approaching 10^{14}/cc, lifetimes have been reduced to minutes, which is obviously unacceptable for long-term space propulsion applications.

Quantum Reflection

Substantial work has been performed in the past few years on creating ultra cold neutral atoms. Laser cooling of cesium atoms has been achieved down to temperatures well below a meV. The DeBroglie wavelengths at these temperatures is hundreds of angstroms. Thus, the neutral atom interaction with the surface atoms in a wall will be a complex many body interaction.

This interaction was first examined in 1936 by J.E. Lennard-Jones and A.F. Devonshire[7]. They predicted at the time the possibility of "quantum reflection." Quantum reflection predicts that in the limit as the energy of a particle approaching the wall of a container gets near zero, the probability of "sticking" to the wall approaches zero. Classically, the sticking probability, S, is predicted to approach unity but quantum mechanics predicts just the opposite solution, i.e that:

$$S \propto \sqrt{E}$$

Measurements[8] have been made for atomic hydrogen at millikelvin temperatures that support the quantum reflection theory[9]. Whether ultracold antihydrogen atoms will reflect from a wall is an open question but could dramatically decrease loss rates in a trap. In addition, we have pursued the idea of creating a two-dimensional Bose-Einstein Condensate[10,11] on the surface of a liquid helium layer to enhance the quantum reflection mechanism. Whether quantum reflection will occur for an antihydrogen atom is not clear.

Proposed Experiments

Synergistic Technologies has completed the design of a solid-state degrader system that will accept a high energy antiproton beam and output a low-energy beam. Computational simulation of a variety of configurations of the device over a range of incident energies shows that production efficiencies as high as 10^{-5} can be expected. Current accelerator technology could produce a low energy beam with near 100% efficiency but would require $10M and five years to build. The degrader system will allow a source of trappable antiprotons to be available within two years. The objectives of our current Phase II SBIR are to construct the degrader system matched to the beam conditions existing at the Fermi National Accelerator Laboratory and to confirm and verify performance and operations. Based on the operational conditions at FNAL, we expect to provide around 1.7×10^{6} antiprotons per hour for research directly or for injection into portable Penning Traps for off-site research. By the end of the project, we intend to provide a potentially commercial source of low energy antiprotons in portable traps to the research community.

Using the degrader system and the HiPAT from NASA MSFC, we propose to perform proof-of-concept experiments of the Parelectricity and Quantum Reflection concepts. The HiPAT will be used to produce a low temperature source of antiprotons or antihydrogen atoms. The particles will be transferred into a test cavity which has a thin layer of either solid ammonia or liquid helium covering the walls. Lifetimes and annihilation location will easily reveal if the particles are being reflected or are annihilating with the wall material.

Summary

We have identified two mechanisms that may enable high density storage of antimatter. The first indicates that if antiprotons are kept in a container lined with frozen hydrogen at less that 0.77 K temperature, they will not annihilate as long as the lining is kept in a (2,1,0) population inversion in the presence of a modest magnetic field. Theorized decades ago, the possibility of quantum reflection may reduce the probability of annihilation of antihydrogen atoms on the surface of any container.

In both approaches, we have adopted a slightly altered strategy. Originally, our goal has been to find methods to increase the particle density in order to increase storage. This was the motivation in examining the storage of antihydrogen. However, the idea of developing a reflecting wall also has tremendous potential. By removing the possibility of loss of the antiparticles by wall collisions, we may be able to make the entire volume of the traps into active storage region. This allows a tremendous increase in storage capacity of the Penning

Trap even though the particle density has not changed over current levels. Both of these concepts could enable systems with ultra-high energy density to be developed. Proof of concept experiments have been designed and may be completed within the next few years.

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