Controlled Antihydrogen Propulsion for NASA’s Future in Very Deep Space¹

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Abstract

To world-wide notice, in 2002 the ATHENA collaboration at CERN (in Geneva, Switzerland) announced the creation of order 100,000 low energy antihydrogen atoms. Thus, the concept of using condensed antihydrogen as a low-weight, powerful fuel (i.e., it produces a thousand times more energy per unit weight of fuel than fission/fusion) for very deep space missions (the Oort cloud and beyond) had reached the realm of conceivability. We briefly discuss the history of antimatter research and focus on the technologies that must be developed to allow a future use of controlled, condensed antihydrogen for propulsion purposes. We emphasize that a dedicated antiproton source (the main barrier to copious antihydrogen production) must be built in the US, perhaps as a joint NASA/DOE/NIH project. This is because the only practical sources in the world are at CERN and the proposed facility at GSI in Germany. We outline the scope and magnitude of such a dedicated national facility and identify critical project milestones. We estimate that, starting with the present level of knowledge and multi-agency support, the goal of using antihydrogen for propulsion purposes may be accomplished in ∼ 50 years.

1 Introduction

In this century, the development of missions to deeper and deeper space will become an ever increasing priority. To complete a mission within a reasonable time frame, even to the nearest extra-solar system objects of interest, the Oort Cloud or the Alpha Centauri star system (4.3 light years away), the velocity of the spacecraft needs to be high, up to more than 10% of the speed of light. To achieve this one needs the highest energy-density fuel conceivable. This would be antimatter; a large amount of it and in a compact form.

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Antimatter can produce three orders of magnitude more energy per gram than fission or fusion and ten orders of magnitude more energy than the chemical reactions currently used for propulsion. As a result, it is a prime candidate for use in future exploration beyond the solar system. It also is a candidate for future missions to the edge of the solar system, which now require on the order of 15-20 years after launch just to reach Pluto.

In this talk (MMN) we start with a quick review of both the discovery of and also our understanding of antimatter (Section 2). In Section 3 a description is given of how cold antihydrogen was created in 2002. We point out why this is the only form of antimatter which is practical for deep space propulsion. We then take a side trip into current studies using antiprotons for cancer therapy (Section 4). This side trip is important as medical research may help with the funding necessary to yield large amounts of antimatter. In Section 5 we outline the trail we need to break to obtain the dense antihydrogen that would be needed for deep space travel. We go on in Section 6 with a discussion of what we can do now to start on this path, providing a roadmap towards the goal. Our conclusions follow.

2 History of Antimatter

It turns out that, given quantum mechanics and special relativity, antimatter’s existence is a consequence [1]-[4]. Although there are hints of the possible existence of antimatter in the strong reflection solutions of special-relativity, the complete break though came after Dirac discovered his relativistic equation for the hydrogen atom [5], whose solutions precisely agreed with the observed energy levels.

That is, this equation had four solutions, which could be interpreted as those for particles with energy and internal spin properties

$$\Psi_{\text{Dirac}} \sim \{ +E \text{ spin up}, +E \text{ spin down}, -E \text{ spin down}, -E \text{ spin up} \}.$$  \hspace{1cm} (1)

But the last two solutions had negative energies. This led to a huge controversy which was only resolved when Anderson discovered the positron in 1932 [6, 7]. This is an (anti)particle with the same mass as but opposite electric charge as the electron.

Over the years, the antiproton, the antineutron, and, indeed with the development of modern particle accelerators, all possible forms of antimatter that can be detected have been detected. We have come to understand antimatter theoretically in terms of the CPT-Theorem of modern field theory.

In an intuitive form, the theorem says that if one were to take a motion picture of a physical process and if one then were to change the ”charges” or “internal quantum numbers” of the particles in the movie (C), run the film backwards (T), and look at it in a mirror after rotating oneself by 180° then one would not be able to tell the difference in the laws of physics being seen. Put another way, this theorem states that every particle has an antiparticle with

i) the opposite electric charge,

ii) the opposite internal quantum numbers,
iii) the opposite magnetic moment,
iv) the same total lifetime, and
v) the same (inertial) mass.

Although active searches continue for violations of this theorem, none has been found.

Most importantly for us, if a particle and an antiparticle collide they annihilate each other. For example, if a positron hits an electron, they turn into two high energy gamma rays, each of energy of the rest mass of one particle, 511 keV. Stored antimatter would be, by definition, the most powerful battery per unit mass ever created.

Positrons (antielectrons) are now easily created in the laboratory from $^{22}$Na sources and controlled in Penning traps [8]. With much more difficulty (an efficiency of 1 part in $10^{10}$) antiprotons are created in high-energy accelerators. At CERN in Geneva, Switzerland, these antiprotons have been (again inefficiently) cooled and stored in Penning traps for fundamental physics experiments.

However, these particles are by themselves not viable for antimatter propulsion. The storage volume must be small. Charged antimatter is limited by the Brillouin density [9]

$$n_0 = \frac{B^2}{2\mu_0 mc^2}. \quad (2)$$

For antiprotons stored in a magnetic field using today’s technology, say 6 or even 25 T, this density would be around $10^{11}$ or $2 \times 10^{12}$ cm$^{-3}$, respectively. (This number is itself orders of magnitude higher than the highest antiproton density so far achieved, $\sim 10^6$ cm$^{-3}$ [10] [11].) Thus, charged antimatter is ruled out. This leaves stable, neutral antimatter, i.e., antihydrogen.

Since, as we come to in the next section, cold antihydrogen has now been produced in the laboratory, it has been argued Ref. [12] that a fundamental science program needs to be undertaken to manufacture and control dense antihydrogen, first in the form of a cold dense gas or even a Bose-Einstein Condensate. The long range goal is to eventually obtain condensed antihydrogen, either as a molecular superfluid, a cluster ion, or as a diamagnetic solid. This would allow a compact source of antimatter to be used for deep-space propulsion. But as many have argued, its use would be tremendously powerful [13].

### 3 How Cold Antihydrogen was Created (2002)

As positrons and antiprotons have been produced, then clearly then antihydrogen should also be able to be made. But it was not so easy. Until recently only a few atoms of antihydrogen had been produced at CERN [14] and at Fermilab [15] in high energy collisions. But these were produced at relativistic speeds, much too fast to capture and study. But in late 2002, the ATHENA collaboration announced it had produced the first low-energy antihydrogen atoms (50,000 of them, later more) [16], using antiprotons which had been in a Penning trap that had been extracted from the AD (Antiproton Decelerator) at CERN. The excitement this produced was magnified by coverage in the international press [17].
The general lay-out of the ATHENA experiment is shown in Figure 1. The central portion of the ATHENA apparatus is shown schematically in Figure 2(a), whilst the relevant trap potentials are illustrated in Figure 2(b).

In each antiproton beam extraction, about $10^4$ antiprotons are mixed with about $10^8$ positrons. Once the low-energy antihydrogen atoms are produced, they are neutral and hence no longer is bound in the Penning trap configuration. This means they are free to wonder in the direction of their momentum after creation and they annihilate with normal matter once they reach any matter in the trap, preferentially at the walls. The signal of an event is the simultaneous (within 1 $\mu$s) detection of (i) two back to back 511 keV gamma rays (from the positron annihilating with an electron) and (ii) about three charged pions (from the antiproton annihilating with a nucleon) with the pions’ momenta directions all converging backwards to a single vertex point (to within a few mm) which is on the line of the emitted photons.

In Figure 3, we shown the verification of the creation of antihydrogen by the detection of the annihilation products, preferentially on the walls of the trap.

Shortly after the ATHENA discovery the ATRAP experiment also announced antihydrogen production [19, 20]. It is now the goal of these collaborations working at the AD to cool these antihydrogen atoms even further, to confine them in possibly a magnetic trap, and to perform experiments with them.

This completed a major step on the road to the technology we are envisioning for antimatter deep-space propulsion.
Figure 2: Schematic of the central portion of the ATHENA apparatus and the trapping potential used [16]. (a) Section of the mixing trap and detector showing the cylindrical electrodes and the position of the positron cloud. A typical antihydrogen annihilation event with the emission of three charged pions and a pair of back-to-back 511 keV gamma-rays is shown. (b) The trapping potential on axis is plotted along the length of the trap. The dashed line shows the potential before the antiprotons and positrons are mixed.

4 Not-really-a-side-bar: Antiproton Cancer Therapy

Simultaneously with the antihydrogen experiments at CERN, the low-energy antiproton beam from the AD was being used by the AD-4 collaboration to study the effect of antiprotons on living tissue as a precursor to possible cancer therapy. An advantage of antiprotons over protons or heavy ions is expected from the extra burst of annihilation energy deposited at the stopping point (Bragg Peak). By proper choice of the beam energy this point can be located precisely inside the tumor volume, would give a higher proportion of destruction to the cancer cells vs. the normal tissue the beam went through.

Preliminary results indicate this is true [21] and also that perhaps as few as $10^{10}$ antiprotons could treat a tumor of size about $1 \text{ cm}^3$ [22]. Since present accelerators, such as
the former AC/AA combination at CERN or the future facility at GSI, produce on the order of $10^{14}$ antiprotons/year, this therapy application has entered the realm of being a realistic possibility. State-of-the-art modifications to current accelerator designs could possibly produce a factor 100 more antiprotons.

Such production would make antiproton therapy realizable, and the funds to produce such a source might be reasonably requested from the NIH. As emphasized in Section 6.1, this could lead to a symbiotic funding partnership with NASA. Indeed, discussions to pursue such a source for therapy purposes are already under way.²

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²A straw-man design is currently being studied by the AD-4 collaboration [21].
5 The Route to Dense Antihydrogen and Deep Space Travel

Long term storage of substantial amounts of antimatter must be developed to enable space missions relying on antimatter-based propulsion systems. Although it is clear that ultimately neutral antimatter must be used, up to now, no valid long-term storage concept for large quantities of antihydrogen has been developed. On the other hand, now that cold antihydrogen has been created, the next steps are to capture it and to cool it even further. Designs for the first goal are now being developed at CERN. They concentrate on being able to build a trap that trap the plasmas before combination and yet also trap the neutral antihydrogen afterwards.

This would be done by surrounding the Penning trap configuration with a magnetic quadrupole configuration, yielding a magnetic field

$$\mathbf{B} = B_0 \left[ \hat{z} + \frac{(x \hat{x} - y \hat{y})}{R_0} \right]. \quad (3)$$

with a minimum at its center. One would then use the magnetic dipole force on the antihydrogen atom

$$\mathbf{F}_{\text{mag}} = \mu \cdot \mathbf{B} \quad (4)$$

to trap the atoms in the so-called “low-field seeking states.” (The upper two states in the Hyperfine diagram for the ground state of atomic hydrogen.)

If this difficult work succeeds (and there appear to be no matter-of-principle problems with it) the next goal will be to cool the captured antihydrogen atoms to very low temperatures, perhaps using the Lyman-alpha lasers that are being developed.

The first step in producing dense antihydrogen would be to produce what has been done for hydrogen atoms, a Bose-Einstein Condensate (BEC). BEC confinement of neutral spin-polarized hydrogen atoms at densities up to $5 \times 10^{15} \text{ cm}^{-3}$ has been demonstrated. [23], which is orders of magnitude more dense than the Brillouin storage density limit for charged antiprotons. To make a BEC of antihydrogen would be an individual step, where one could learn the techniques of controlling a relatively large amount of antihydrogen. One also would have to overcome the problem of the antihydrogen transitioning out of the confined states [12]. The clear ultimate goal would be to make very dense antihydrogen, in the form of clusters or solids (perhaps stored diamagnetically).

At present the wasteful method of resonant evaporative cooling is used to achieve the temperatures and densities needed to form a hydrogen BEC. But the development of lasers for direct and efficient cooling of hydrogen atoms has now just started. Efficient laser cooling of hydrogen will revolutionize the methodology of forming, controlling, and studying hydrogen Bose-Einstein Condensates. These studies can all be done with ordinary matter, in preparation for having more copious amounts of antihydrogen available.

If the envisioned progress comes to fruition, laser cooling could then be used in an attempt to efficiently make an antihydrogen BEC. An antihydrogen BEC would be an impor-

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3A BEC is a gaseous coherent quantum system, just as are superfluid helium or superconducting currents.
tant step down a path that could eventually lead to even more dense antihydrogen molecules, liquids, solids, and cluster ions. Indeed, since one might expect the next stage to be going from controlled ultra-cold (below 50 \( \mu \text{K} \)) BEC hydrogen atoms to controlled hydrogen molecules, it is heartening that there is evidence of a hydrogen-molecule superfluid with a critical temperature of 0.15 K. Since the triple point of hydrogen is at 13.8 K, a potential path to denser condensed antimatter becomes more interesting.

6 What Can We Do Now?

A space-certified storage system for neutral antimatter will not be obtained from a linear extrapolation of heretofore existing technologies. Rather, it requires a series of scientific and/or technological breakthroughs. While breakthroughs can never be predicted, they typically will not happen without the definition of a strong need and the challenge presented to the scientific community by a truly ambitious goal.

Meanwhile, many of the underlying issues can be addressed with both the modest supply of antimatter available at this time at accelerator centers worldwide and with the limited means to store the particles. The technological and scientific knowledge gained in these tests will enable us to lay out a path into the future of antimatter-based propulsion systems.

However, the most important item is the need for a dedicated low-energy antiproton source in the United States.

6.1 A dedicated Low-Energy Antiproton Source in the USA

The biggest obstacle to producing copious antihydrogen is the dearth of low-energy antiproton production. As stated, it presently is a very inefficient process and is done only in Europe. At present, the only source of low-energy antiprotons is at CERN. It is hoped that the AD facility at CERN will keep running until perhaps the end of this decade. Then a newly proposed facility, FLAIR (A facility for Low-energy Antiproton and Ion Research), will hopefully be built at the GSI accelerator center in Germany. It could yield \( 10^{12} \text{ Low Energy} \) antiprotons per year.

But the US needs a facility so it can realistically pursue the ultimate goal of copious production of antiprotons leading to copious antihydrogen. It is only with a viable facility that studies can be done that will lead to the necessary break-through technology needed for more efficient antiproton production.

The communities to do this, perhaps as a consortium, are there. The DOE physics community would like such a facility to continue fundamental symmetry studies on antimatter and also to test gravity. As pointed out in Section 4, the work on antiproton therapy would lead to NIH interest in this facility. NASA would have an interest for deep-space flight. There are also other communities that would have an interest: space reactor teams, RTG builders, radiation physicians and physicists, and nuclear and particle experimentalists. A NASA/DOE/NIH consortium to build a dedicated facility would be a natural.
6.2 A Roadmap To Antihydrogen Propulsion

Knowing the cost of acquiring the technological capabilities needed to produce large quantities of antihydrogen atoms, to store them for long periods, and to use them for propulsion purposes in space is, of course, very important. Given our present technological level, our estimates are that:

- It would take about 5 years and $\sim 0.5$ B$ to build a source.
- It would take about the same time and money more to develop antihydrogen handling technologies.

During all this time effort would be given to developing the new antiproton production technology that is needed. Current antiproton production rates are low. While clever techniques can enhance these rates by several order of magnitude and quantities sufficient for advanced concepts can be produced given enough economic and political pressure onto the few available sources, a real breakthrough can only come through continued interest and research in this area. A good analogy is the comparison between a light bulb and a laser. In both cases light is produced, but in one system through thermal heating of a material and in the other through coherent processes. Antiprotons are currently produced by heating a metal target with a primary proton beam. This is a direct analogy to the light bulb — we are still awaiting the invention of a ‘laser-equivalent’ for the production of particles of antimatter.

- A GUESS is that 10-20 years more would be needed for this.

This would be the make or break point. If after 30 years one did not have a new antiproton production technology, then the effort would be abandoned as far as deep-space propulsion is concerned, although not for the other applications. But with success,

- A BIGGER GUESS is that it would take 10-20 more years to develop a real system.

Note that much of the technology will be standard in the sense that the power transfer from antimatter to thrust has long been a problem of interest [3, 28], as well as that of obtaining thrust from other nuclear mechanisms [29, 30].

So, we are talking of about 50 B$ over 50 years. That period is like the time from vacuum-tube computers to the microchip processors of today. It would be a viable time frame - if it works. But most importantly, antimatter science has now advanced to the point where antimatter technology has left the realm of science fiction and has reached the first stages of reality.\textsuperscript{4}

7 Conclusions

The road we have described is challenging both scientifically and technologically. Enormous scientific and technological barriers have to be overcome. But the potential intellectual and societal rewards, even along the way, are enormous.

Antimatter-matter annihilation is one of the prime candidates to achieve the high specific

\textsuperscript{4}Indeed, if one considered positron emission tomography (PET), the reality arrived some time ago.
impulse i) desired for the challenging missions of exploring the Heliopause and visiting the Oort Cloud, and ii) needed if we plan to attempt a rendezvous with the nearest star systems. While no clear pathway to the necessary technologies exists, experimental development in the normal matter world of laboratory-sized research equipment can help us to reach these most ambitious goals, *IF* we simultaneously embark on constructing a dedicated low-energy antiproton facility.

It behooves us to now embark on extensive, serious work on the possibilities that are before us. To achieve them quickly it is necessary to set ourselves in motion now.

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