COMMERCIAL PRODUCTION AND USE OF ANTIPROTONS

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Abstract

The production of commercial quantities of antiprotons has been a reality for many years now. The deceleration and trapping of antiprotons is a relatively new activity, but has been sufficiently proven to be translated into a business enterprise. Now that NASA has developed a portable Penning trap and accompanying vehicle for transporting antiprotons, all the elements are in place to begin the commercial distribution of antiprotons. The list of potential customers for antiprotons is continuously growing, with market analyses already performed on some medical, propulsion, and physics research applications. In this talk these applications are reviewed along with their appetite for antiprotons. In addition, some ideas aimed at expanding present production capabilities will be proposed.

1 INTRODUCTORY REMARKS

Science fiction stories and movies use antimatter to cause explosion or drive massive manned starships. This is the mental picture which students, investors, government leaders, and everyone else in the general public initially view attempts to bring antimatter out into the general economy.

In promoting an enterprise whose goal it is to commercialize antiproton production, distribution, and usage, it is therefore imperative to propose and execute a realistic and sincere plan in which the scientific method is scrupulously applied at all times. Without this discipline, especially in the area of medical therapy using antiprotons, one is doomed to being labeled crazy or criminal.

There is a legal framework within which such an enterprise must operate; this is the world of intellectual property and trade secrets. Many of the devices and processes that we take for granted in accelerator laboratories are being patented, sometimes by people who have never seen an accelerator.

In fact, there exists a group of people in the United States who asked a U.S. Federal Court judge to restrain me from giving this talk. Their reason is that I might reveal trade secrets they claim to possess in the areas of antiproton production, distribution, and most medical applications. This is despite the fact that they have never seen nor handled an antiproton, and there is no evidence that any of the applications of antimatter yet envisioned will actually work. Given that the talk was given and this paper was written, one can successfully conclude that the judge did not rule in this group's favor. Nonetheless, there is a significant and expensive lawsuit now active in the United States on the topics described in this paper.

2 ANTIPROTON PRODUCTION

At present there are two high-energy physics laboratories on the planet that produce antiprotons in sufficient quantities to be useful in a commercial enterprise. More production facilities are envisioned, and any company that wishes to buy antiprotons must secure a copious and reliable source. Figure 1 contains a diagram of the various options that Hbar Technologies LLC is pursuing to secure such a source.

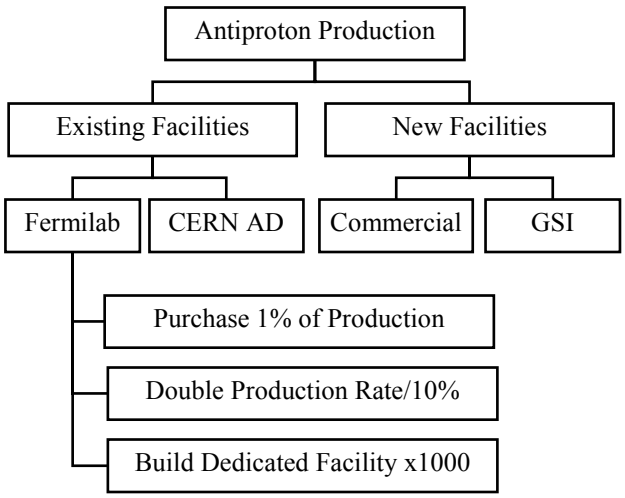

Figure 1: Diagram of the present and future options for antiproton production capable of satisfying the demand from commercial applications.

2.1 Existing Facilities

The CERN Antiproton Decelerator (AD) [1] is at present the only facility at which slow and stopped antiprotons are available. The design intensity of 6×10^8 antiprotons/hour and anticipated operational schedule of 3000 hours/year yield only enough antiprotons for proof-of-principle experiments required prior to the commercialization of any proposed antiproton application.

The Fermilab Antiproton Source [2] has been recently upgraded and has demonstrated the production of 1×10^{11} antiprotons/hour. It has also demonstrated over the years an average operational schedule of 4500 hours/year. This is 250 times the annual production quoted at the CERN AD. Unlike the CERN AD, which can decelerate the antiprotons down to 100 MeV/c, Fermilab operationally produces and accelerates antiprotons from 8.9 GeV/c.

Although deceleration of antiprotons has been demonstrated in the Antiproton Source [3], this process is cumbersome and highly disruptive to antiproton production. More recently it has been shown that

antiprotons can be decelerated in the Fermilab Main Injector down to a momentum of 3 GeV/c [4].

2.2 New Facilities

An ambitious plan for upgrades at GSI [5,6] envision the capability of producing antiprotons at approximately the same production rates presently achieved at Fermilab. This plan has not yet been approved by the German government.

It is of course possible for other laboratories around the world, in New York, New Mexico, Russia, and Japan, to produce antiprotons. But in each of these cases, the expenditures required to achieve the production rates found at Fermilab or envisioned at GSI would require on the order of 100 M$ or more.

Ultimately, if the hypothesized commercial applications of antiprotons are confirmed, there will be far more demand for antiprotons than global supply. Inevitably a dedicate commercial factory for antiproton production will need to be constructed.

2.3 Hbar Technologies LLC Scenario

Hbar Technologies LLC [7] envisions a staged approach to business development in which proof-of-principle experiments aimed at validating antiproton application concepts are completed before more ambitious stages are launched. These experiments could take place either at the CERN AD or on a low-cost beamline constructed off the Fermilab Main Injector.

Informal discussions with the Fermilab management have centered on the concept of purchasing approximately 1% of their production. In preparation for such a request, Fermilab has estimated that the cost it must charge private companies for antiprotons is 27.4 M$/year for every antiproton produced. Therefore, if Hbar Technologies LLC were to purchase 1% of the antiprotons produced in a given year, it would need to pay Fermilab 274 k$.

In order to build such a preliminary facility, it would be necessary to decelerate antiprotons to 2 GeV/c, though preferably 0.73 GeV/c (corresponding to a kinetic energy of 250 MeV). It has been pointed out by Bruce Brown of Fermilab that the field quality of the new Main Injector dipole magnets is sufficient to maintain hope that deceleration to 250 MeV is possible. The biggest obstacle to Main Injector deceleration is diminishing longitudinal bucket area using the existing RF stations [4].

Between the proof-of-principle experiments and the high-growth stage of an antiproton business enterprise there is probably too little money yet available for construction of a dedicated production facility. For this reason a business plan has been developed in which a larger fraction of antiprotons are purchased from Fermilab in exchange for work on increasing the antiproton production rate with the existing Antiproton Source [2]. Methods for increasing the antiproton production rate are increased proton intensity on target, proton bunch shortening on target, improved target geometries and materials, improvements in antiproton capture and cooling, and operational enhancements of the overall Tevatron Collider complex to more efficiently utilize antiprotons for generating high luminosity [8]. It might be expected that up to 10% of this enhanced antiproton production rate would be available to Hbar Technologies LLC. Note that for those upgrades that involve efficiency improvements, the energy and labor costs that dominate the cost of antiprotons would remain largely unchanged. Therefore, these upgrades would have the additional effect of reducing the price per antiproton.

Before buying land and building a proton source, linac, and one or two synchrotrons for generating the high energy protons required for antiproton production, it may be more cost effective to remain at an existing laboratory such as Fermilab and build a new antiproton target, capture, cooling, and deceleration facility.

The goal is to produce a facility that optimizes the process of antiproton capture, deceleration, and trapping. The first step is to leave behind design preconceptions stemming from preceding facilities. This is because these antiproton production scenarios were based on the assumption that one wanted antiproton bunches for proton-antiproton collisions. The longitudinal phase-space requirements for this applications are dramatically different from those where trapped antiprotons are the goal.

For example, it was calculated [9] that the optimum production scenario might involve recirculating protons through a thin target. Imagine a farm of large transverse bore capture/precooling traps that accepted a quasi-continuous antiproton stream with a 10 keV full-width energy acceptance. Assume that the protons are accelerated in a synchrotron which has a 0.5 sec ramp time. The total antiproton longitudinal phase space area per spill is therefore 5 keV-sec. Let us further assume that the antiprotons are produced when each of 500 proton bunches is individually directed onto a thin target for 100 turns. In a 120 GeV stretcher ring the same circumference as the Main Injector this process would take 500 x 100 x 10 μsec or 0.5 sec. Assuming that capture and deceleration are implemented via a series of linear decelerations and bunch rotations to progressive lower RF frequencies (and larger transverse bores), no intermediate cooling would be required. Throwing in a factor of 10 emittance dilution, the initial antiproton energy spread that must be captured after the transition of 1 nsec full-length proton bunches through the thin target would be 5000 ev-sec x 10 / 500 / 100 / 1 nsec = 1 GeV full width. Given that antiprotons are generated at 8 GeV, this represents an inial capture bandwidth of ±6%. This is very close to levels already achievable, and much smaller than values assumed by design studies such as those for the muon collider. This idea seems to work on paper with a factor of 1000 increase in antiprotons, though the construction cost probably exceeds 1 B$. If the applications for antiprotons are as compelling as envisioned, revenues from antiproton sales would allow this capital investment to be repaid in just a few years.

3 ANTIPROTON TRANSPORTATION

Within the past decade Penning traps have been built to hold antimatter [10,11]. Experiments at CERN have demonstrated the ability to hold antiprotons in Penning traps. In 1991 Gabrielse, et. al. [10], trapped and held 100 antiprotons for several months. In 1994 Holzscheiter, et.al. [11], trapped 10^6 antiprotons. In 1998, NASA supported Dr. G. Smith et al.[12] at Pennsylvania State University (PSU) to build a trap to hold between a 10^8 and 10^{10} antiprotons. The PSU trap weighs about 200 pounds and can thus be transported to any desired location. In 1999, James Martin at the NASA Marshall Space Flight Center built the High Performance Antimatter Trap (HiPAT). HiPAT has the design capacity to hold 10^{12} antiprotons for several weeks.

Hbar Technologies LLC will lease the HiPAT trap in order to transport antiprotons. At present proton commissioning is taking place to validate the capacity of the trap. In parallel, U.S. Department of Transportation regulations are being negotiated to handle the transportation of antiprotons on specially built trucks or aircraft. This is a very special problem for regulators; under normal conditions there is very little radiation, so it is not a typical radioactive source. On the other hand, if there is an accidental mass-annihilation of the antiprotons, more than 1 Rad of radiation will be briefly emitted.

Most medical applications for antiprotons are hypothesized to require approximately 10^{10} antiprotons per patient. Assuming that 20 patients could be treated per day, this means that each trap holds roughly one week's worth of antiprotons. A delivery truck bringing a fresh trap of antiprotons once per week would not be unusual given the similar frequency of helium and nitrogen deliveries to most state-of-the-art hospitals today.

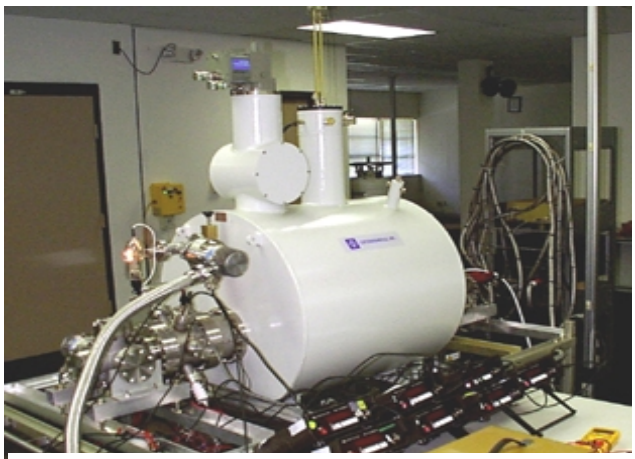

Figure 2: Picture of the NASA HiPAT trap designed to transport 10^{12} antiprotons.

In the farther future, it will be necessary to transport larger amounts of antimatter. Assuming that the formation of neutral hydrogen atoms is an imminent success at the CERN AD, it will be necessary to extrapolate this work toward far more efficient and prodigious methods of antihydrogen formation and capture. Some preliminary ideas for such robust antihydrogen formation mechanisms have recently been identified in April of 2002. Experimental verification using hydrogen formation will be the subject of intense discussions with potential collaborators in the coming months.

4 ANTIPROTON APPLICATIONS

The field of particle physics discovered and used antimatter during its trail of discovery. To date antiprotons have also been used as probes to discover the internal structure of nuclei, and will hopefully be used soon for atomic physics and grand unified theory (GUT) tests. Perhaps antihydrogen will be used to verify that the gravitation force between matter and antimatter is repulsive, and not attractive.

In this paper commercial applications are stressed. As can be seen in the diagram in figure 3, all of the presently hypothesized commercial applications are in the field of medicine.

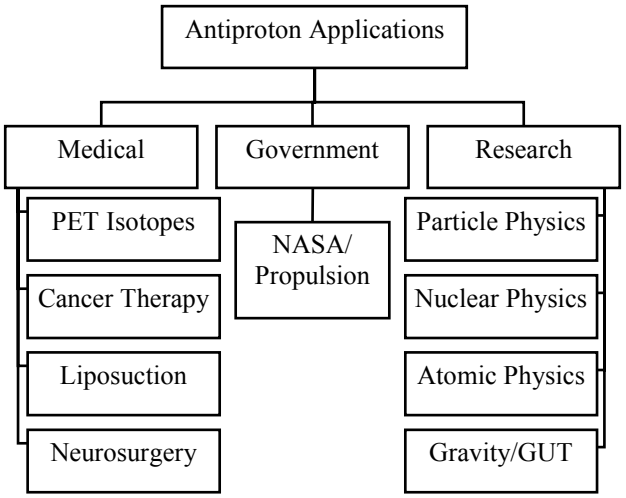

Figure 3: Diagram of the various categories of antiproton applications. The strongest commercial possibilities are in the field of medicine.

4.1 PET Isotope Production

Publications for at least the past decade [13-19] show PET techniques being used to diagnose head tumors, breast masses, serotonin uptake, pancreatic cancer, cerebral glucose consumption, coronary artery disease, and regional blood flow to name a few examples. The basis for PET is that isotopes such as carbon-11, oxygen-15, and flourine-18 emit positrons as part of their natural decay chain. The half-lives of these isotopes are 10 minutes, 2 minutes, and 120 minutes respectively. Although radioactive, the isotopes chemical behavior is identical to the stable versions of the element-- carbon-12, oxygen-16, and flourine-19.

Nieweg [15] and others [18,19] have shown that flourine-18 labeled floro-deoxyglucose (FDG) has been effective in locating small breast tumors. The process relies on the observation that cancerous cells maintain a substantially higher metabolic rate than normal tissue. Consequently, sugars such as deoxyglucose are more readily absorbed and integrated into the cell structure. Currently, FDG is widely used for clinical treatment due to the long half-life of the flourine-18. Shorter half-lived isotopes such as oxygen-15 or carbon-11 are equally useful for PET imaging but have been unavailable for clinical treatment due to the lack of a source and the difficulty in rapidly transporting the samples to the patient. If available, however, carbon-11 and oxygen-15 could have superior performance in that they will have a higher specific activity (disintegrations/sec) which will improve signal to noise ratios. If a source of oxygen-15, carbon-11, or deoxyglucose composed of either of these elements could be developed, the efficacy, utility, and availability of PET diagnostics could be revolutionized.

The creation of a radioisotope requires the removal of a nucleon from the nucleus of a stable target. Historically, the removal has been achieved by bombarding the target with a beam of particles such as protons of sufficient energy to "knock out" a nucleon. Because of the binding energy holding the nucleon in the nucleus, the bombarding particles kinetic energy must be around 8 MeV or greater. Conversely, an antiproton annihilating against the neutron of a carbon, oxygen, nitrogen, or fluorine nucleus will generate a PET isotope.

Because large and radioactive proton or ion accelerators are not practical in most hospitals, PET isotopes such as these generated by streaming antiprotons from a trap into a suitable target would have quite an advantage by producing isotopes at the patient bedside.

4.2 Cancer Therapy

The stopping of antiprotons in matter has been well researched [20-24]. The probability of annihilation as a function of kinetic energy has been measured by many experiments. In addition, measurements of the energy-loss rate of antiprotons in a variety of media have been reported over the past forty years. The combination of these data sets allows the antiproton annihilation rate to be calculated. These calculations show that an antiproton entering a human body with an incident energy of 250 MeV or less will have only a 5% chance of annihilating before coming to a full stop in the tissue. Initially, the antiproton will deposit very little energy to the intervening tissue as it slows. Thus, a beam of antiprotons will traverse a known depth of tissue and come to rest at a precisely determined location in the body, at the location of the Bragg peak. Once the antiprotons have stopped, they will capture into the nuclei in the region and annihilate. The products of the annihilation reaction have been well characterized and consist of three charge pi-mesons and two neutral pi-mesons, on average. The pi-mesons have large kinetic energies and will depart from the annihilation region without deposition of significant levels of radiation damage to the surrounding tissue.

In 1984, Kalogeropoulos [25] first reported measurements of antiprotons stopping in tissue-simulating material in order to demonstrate the ability to image the region where the antiprotons stopped. This was the first published work on using antiprotons to deposit large levels of energy in localized regions. In 1985, Sullivan [26] reported measurements of the energy deposited by the annihilation of antiprotons in tissue-simulating material as seen figure 4. The results indicated that a recoil nucleus with about 30 MeV kinetic energy was produced in the interactions. In 1989, Kalogeropoulos [27] reported further work in modeling the energy deposition in plastic material to simulate tissue.

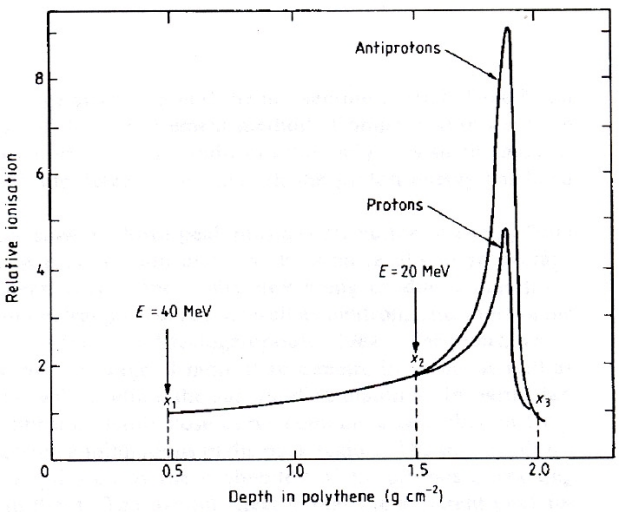

Figure 4: Figure taken from refrence [26], showing the relative energy deposition between protons and antiprotons in tissue-like material.

The key to antiproton therapy is the production of this recoil heavy ion. The ion will be produced with several MeV of kinetic energy and will have a charge state of several electron charges. As the ion transverses the cells in the tumor, it will lose energy to the surrounding atoms, producing a path of highly ionized ions and free radicals in the cell. These free radicals can migrate and chemically react with the DNA molecules causing them to break.

When the antiproton annihilates against the neutron of a carbon, nitrogen, or oxygen nucleus, a PET isotope is generated. Imagine treating a patient within a modern PET scanner. During treatment with antiprotons, PET isotope production in the cancer growth will provide feedback on dose intensity and position. In addition, by firing a low intensity pre-pulse of antiprotons before each lethal pulse and determining the position of the PET isotope distribution from the pre-pulse before firing the lethal pulse, the construction of hyper-accurate and expensive beam delivery magnet systems "gantries" and extensive patient fiducialization is no longer necessary. Finally, by recording the output from the real-time PET

image reconstruction software, oncologists and therapists will have a record of precisely where the prescribed dose was sent. This should prove to be a powerful tool against malpractice lawsuits that can inhibit the acceptance of new yet powerful tools against cancer.

4.3 Liposuction and Neurosurgery

In the case of cancer therapy, antiprotons were used to kill cells that are normally immortal. There are other types of immortal cells that one might consider killing. Two examples are fat cells (adipose tissues) and cartilage.

Inducing programmed cell death (apoptosis) in adipose tissue using a noninvasive method might have the advantages of lower risk of death and lack of bruises and scars. Hollywood movie stars alone would probably make this a very profitable business enterprise.

Inducing apoptosis in cartilage, such as spinal disks, might be used to remove pressure from pinched nerves and other forms of neurological relief. This business market might be larger than all of the above combined.

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