Antimatter induced fusion and thermonuclear explosions*

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Abstract

The feasibility of using antihydrogen for igniting inertial confinement fusion pellets or triggering large-scale thermonuclear explosions is investigated. The number of antiproton annihilations required to start a thermonuclear burn wave in either DT or Li_2DT is found to be about $10^{21}/\kappa^2$, where κ is the compression factor of the fuel to be ignited.

In the second part, the technologies for producing antiprotons with high energy accelerator systems and the means for manipulating and storing microgram amounts of antihydrogen are examined. While there seems to be no theoretical obstacles to the production of 10^{18} antiprotons per day (the amount required for triggering one thermonuclear bomb), the construction of such a plant involves several techniques which are between 3 and 4 orders of magnitude away from present day technology.

Considering the financial and energy investments needed to produce antimatter, applications will probably remain confined to the military domain. Since antihydrogen-triggered thermonuclear explosives are very compact and have extremely reduced fallout, we conclude that such devices will enhance the proliferation of nuclear weapons and further diffuse the distinction between low-yield nuclear weapons and conventional explosives.

1 Introduction

Matter-antimatter interaction produces more energy per unit mass than any other means of energy production. For example, proton-antiproton annihilation releases

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275 times more energy in the form of kinetic energy of charged particles than nuclear fission or DT fusion. This energy is released by simple contact of antimatter with matter so that, in principle, no ignition energy is required to start the reaction. It is therefore not surprising that the concept of using antimatter as an energy source has been in scientific literature for decades [1, 2].

Other practical applications of antimatter are under consideration. For example, antimatter propulsion systems [3], space based power generators [4], directed energy weapons [4],[1] and cancer therapy [5, 6]. Finally, both *Edward Teller* [7, 8, 9, 10] and *Andrei Sakharov* [11], the key scientists in charge of the development of the H-bomb in their respective countries, show in their published scientific works a big interest in the annihilation properties of antimatter, the nuclear process that after fission and fusion could lead to a third generation of nuclear bombs.

This paper is a summary of a comprehensive assessment of the feasibility of producing large quantities of antiprotons and using them for igniting inertial-confinement fusion pellets or triggering large-scale thermonuclear explosions [12]. In sections 2 to 6 we evaluate the number of antiprotons needed to start a thermonuclear detonation wave in either DT or a Li_2DT mixture. In Sections 7 to 11 we examine the problems of producing, collecting, cooling, manipulating and storing the required amounts of antiprotons and antihydrogen.

2 Matter-antimatter annihilation

When a particle meets it's antiparticle they annihilate and the energy equivalent to their total mass ($2mc^2$) is converted into various new particles and kinetic energy [13]. In the case of proton-antiproton annihilation, many different reaction channels are possible, each resulting in the production of a different number of charged and neutral particles. A good approximation is that three charged and two neutral pions are produced on the average. Since neutral pions quickly decay into photons, the typical $p\overline{p}$ annihilation process is as follows:

$$p + \overline{p} \rightarrow 3\,\pi^{\pm} + 2\,\pi^{0} \rightarrow 3\,\pi^{\pm} + 4\,\gamma, \tag{1}$$

where $E_{\pi}^{\pm} = 236$ MeV and $E_{\gamma} = 187$ MeV. An antiproton can also annihilate with a neutron, in which case mostly pions are produced again, in numbers, on the average, similar to $p\overline{p}$ annihilation.

[1] Directed energy weapons applications may include the projection of plasma jets, X-ray or gamma-ray laser pumping, and antimatter beams.

Antiprotons, antineutrons and positrons can combine to form antinuclei, antiatoms, antimolecules. Annihilation occurs when the two kinds of matter come sufficiently close to one other. Even at some distance, a neutral atom and a neutral antiatom will attract each other by van der Waals forces [10, 13]. As a consequence, storage of *antiatoms* in a container made of matter is impossible in general. However, there may exist metastable states of *antiprotons* in normal matter [14], and $\overline{p}$'s may possibly be stored in superfluid helium [14], a speculation encouraged by the fact that helium is the only atom which, theoretically, cannot capture a low energy antiproton [15].

3 Plasma heating with antiprotons

When a $\overline{p}$ annihilates in a hydrogen plasma, essentially all the annihilation energy is radiated in the form of very energetic pions and photons. At solid hydrogen densities, the mean free path of the 187-MeV photons is 25 m, so that they will not loose energy in the plasma. However, the three 236-MeV charged pions will loose energy by multiple Coulomb interactions with the electrons at a rate approximately given by: $dE/dx = 0.52$ MeV/cm in solid H_2 or DT and 2.06 MeV/cm in Li_2DT.

If we now assume that annihilation takes place at the center of a sphere, the energy dW deposited within a radius $R = 1$ cm is only 1.5 MeV out of the total 1876 MeV annihilation energy. There are however several ways to improve energy deposition, and thus plasma heating. Firstly, the fuel to be heated may be compressed by a factor κ, dE/dx will then be multiplied by κ, and thus dW by $\kappa^{2/3}$. But compression requires energy. Secondly, fuels such as Li_2DT, which contain more electrons, have a proportionally larger dE/dx. However, their thermonuclear ignition temperature is also higher. Finally, annihilation may take place with a nucleus.

When a $\overline{p}$ annihilates with a nucleon from a nucleus, because of the Fermi motion of the annihilated nucleon, the nucleus will recoil with an energy of about 20 MeV. Furthermore, each of the 5 annihilation pions has a probability of colliding with the rest of the nucleus. Hence, the average total energy deposition in a sphere is

$$dW = \nu \frac{dE}{dx} R + \epsilon, \tag{2}$$

where $\nu = 3$ is the number of charged pions and ϵ the local energy deposition by the recoiling nucleus and the various pion-nucleus interaction debris.

In the case of $\overline{p}$ annihilation with deuterium or tritium ϵ is approximately 12 MeV on the average, about half of the energy corresponding to the Fermi momentum. With heavy nuclei there have been many theoretical speculations in the absence of measurements. The first of these was introduced by *Duerr* and *Teller* [9], who speculated that an antiproton would find a very strong (900 MeV) attractive potential when getting close to a nucleus. More recently [16], Los Alamos scientists have calculated that annihilation in carbon would result in the local energy deposition of about 100 MeV. Recent measurements at CERN show that it is in fact only 33 MeV in carbon [6], and approximately 55 MeV in silicon [17]. Low energy $\overline{p}$'s annihilate mostly at the surface of nuclei, and thus local energy deposition follows a $A^{2/3}$ dependence on atomic weight. In effect, the CERN data is compatible with the expression :

$$\epsilon \approx 6.4 A^{2/3} \quad \text{[MeV]}. \tag{3}$$

Hence, for $\overline{p}$ annihilation in H_2, DT or Li_2DT, ν is always about 3 and ϵ is approximately equal to 0, 12 or 22 MeV respectively.

4 Thermonuclear burn of a particle-antiparticle plasma

A matter-antimatter plasma is obtained if some initially stable particle-antiparticle mixture is suddenly ignited. The annihilation rate of two interacting species, with number densities n and $\overline{n}$, is

$$\frac{d\overline{n}}{dt} = -n\overline{n}\langle\sigma v\rangle, \tag{4}$$

where $\langle\sigma v\rangle$ is the annihilation reaction rate averaged over the Maxwell distribution. Fig. 1 gives $\langle\sigma v\rangle$ for $e\overline{e}$ and $p\overline{p}$ plasmas.

In a $H - \overline{H}$ plasma, equation (4) holds for both protons and electrons with $n = \overline{n} = n_0 = \rho\mathcal{N}_A/2$ initially. Hence, for a given temperature

$$n = \frac{n_0}{1 + t/\tau} \qquad \text{with} \qquad \tau = \frac{2}{n_0\langle\sigma v\rangle}. \tag{5}$$

If we assume $T = 20$ keV, $\langle\sigma v\rangle$ is approximately the same for both e^+e^- and $p\overline{p}$ annihilation. Thus the electron and the proton populations deplete at the same rate, with a time constant of 5 ns for $\rho = 0.07$ g/cm^3.

5 Annihilation in a matter-antimatter boundary layer

When matter and antimatter come into contact, annihilation primarily takes place in a boundary layer in which particles and antiparticles are mixing. The thickness

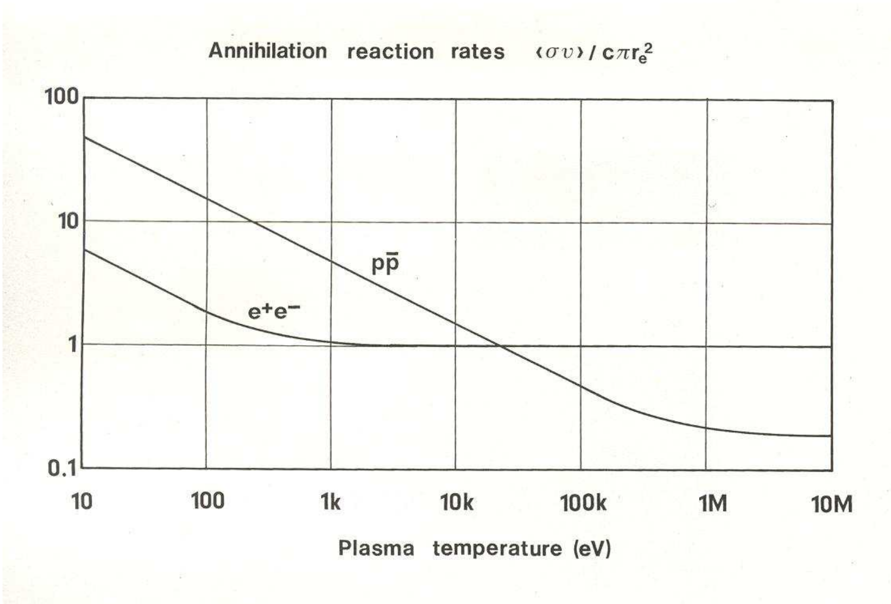

Figure 1: Electron-positron and proton-antiproton annihilation reaction rates averaged over the Maxwell velocity distribution.

of this matter-antimatter plasma is of the order of the antimatter mean-free-path in matter, i.e., $(3n\sigma)^{-1}$. A first approximation, assuming that whenever an antiparticle penetrates into the boundary layer it instantly annihilates, is an annihilation rate per element area given by the total number of antiparticles impinging on that surface. From the Maxwell velocity distribution one gets

$$\frac{d\overline{N}}{dS\,dt} = -\overline{n}c\sqrt{\frac{kT}{2\pi mc^2}}. \tag{6}$$

The e^+ annihilation rate is thus $\sqrt{m_p/m_e} \approx 43$ times the $\overline{p}$ annihilation rate. However, since the $\overline{H}$ plasma Debye length is much smaller than the boundary layer thickness, plasma charge neutrality insures that the antimatter flow rate is determined by the slowest annihilation rate. Therefore, if $\overline{H}$'s interact with the walls of a closed cavity, annihilation results in an overall decrease of the antimatter density within the cavity.

Let us now take the case of a sphere of solid antihydrogen that is suddenly put in contact with a collapsing spherical shell of compressed DT (see Fig. 2). To solve Eq. (6) one has to calculate the increase in the $\overline{H}$ plasma internal energy by the pions and other particles from $\overline{p}$ annihilation in the surrounding DT:

$$dW = -dN\frac{1}{2}\Big(\nu\frac{dE}{dx} + \frac{\epsilon}{\lambda}\Big)\frac{4R}{\pi}\frac{N}{N_0}, \qquad (7)$$

where $\lambda = 3$ cm is the approximate range of the 20-MeV recoil protons from $\overline{p}$ annihilation in DT, and N (initially equal to N_0) the number of $\overline{H}$ atoms. For hydrogen $dW = 3NkdT$, we get a system of equations for the $\overline{H}$ plasma density and temperature. If annihilation is much faster than the collapse of the cavity, R remains constant and the solution of Eqs. (6) and (7) is

$$T = T_1 \tanh^2(t/\tau_a), \qquad (8)$$

and

$$N = N_0\Big(1 - \tanh^2(t/\tau_a)\Big). \qquad (9)$$

For $N_0 = 10^{18}$, which corresponds to $R = 0.02$ cm, we find $T_1 = 19$ keV and $\tau_a = 0.25$ ns. Thus, in about $2\tau_a = 0.5$ ns, over 90% of the antihydrogen in the sphere is annihilated. This time constant is compatible with the requirements of instantaneous thermalization and inertial confinement of the plasma.

6 Antiproton triggered thermonuclear detonation wave

The most efficient way to trigger a thermonuclear explosion is probably to start a thermonuclear detonation wave in Li_2DT by collapsing a hollow sphere of that material on a tiny spherical pellet of solid antihydrogen (Fig.2).

In the spark model of thermonuclear ignition [18], an outgoing spherical detonation wave starts if : (a) a critical amount of energy E_c is deposited in the center of the sphere (the "spark" region) and (b) if the temperature within this volume is higher than a critical temperature T_c. Without compression, one has $E_c = 5 \times 10^{25}$ keV and $T_c = 4$ keV for solid DT , and $E_c = 3 \times 10^{26}$ keV and $T_c = 13.6$ keV for Li_2DT. However, for a compressed thermonuclear fuel at temperature T_c, the critical energy decreases with the square of the compression factor κ.

The number N of $\overline{p}$ annihilations necessary to induce a thermonuclear burn wave can be estimated by supposing that annihilation takes place at the center of the sphere to be ignited. Thus, from equation (2), condition (a) is satisfied if

$$E_c/\kappa^2 = N\Big(\nu\frac{dE}{dx}\kappa R_s + \epsilon\Big). \qquad (10)$$

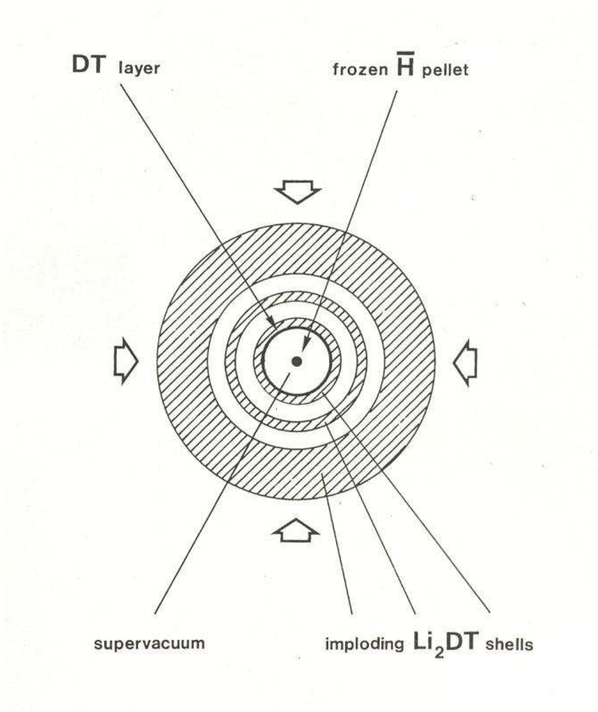

Figure 2: Ignition of a spherical thermonuclear detonation wave in Li_2DT. A series of concentric shells are imploded by chemical explosives or by other means. When the innermost shell gets into contact with the levitated antihydrogen pellet, annihilation produces sufficient energy to trigger a thermonuclear burn wave in the bulk of the Li_2DT fuel. The multishell structure avoids excessive preheating of the antihydrogen pellet during implosion.

Since the pions originate from the center, the temperature in the fuel goes as $1/r^2$. Therefore, for simplicity, we require that condition (b) is satisfied for the average temperature within the critical volume. Thus

$$E_c/\kappa^2 = \frac{3}{2}\frac{z}{a}\kappa\rho N \frac{4\pi}{3} R_s^3 kT_c, \tag{11}$$

where z and a are respectively equal to 2 and 2.5 for DT, and 6 and 9.5 for Li_2DT. Taking $\kappa = 30$, a modest compression factor, and solving Eqs. (10) and (11) for N and the spark radius R_s, one finds $N = 3 \times 10^{18}$ and $R_s = 0.09$ cm for DT, and $N = 6 \times 10^{18}$ and $R_s = 0.07$ cm for Li_2DT. However, because of some of the simplifying assumptions made, these results may be somewhat pessimistic. Hence, we will assume that 10^{18} $\overline{p}$'s are sufficient to trigger the thermonuclear explosion of compressed DT or Li_2DT pellets.

For thermonuclear explosions in the kiloton range, chemical explosives may be used to implode the Li_2DT shells. For low yield explosions such as in X-ray laser pumping or inertial-confinement fusion (ICF), compression factors higher than 30 can be achieved using magnetic compression, beams or other techniques. However, antiproton induced fusion will remain an attractive alternative to normal ICF only if the compression factor is kept relatively small, i.e., less than 300, giving a number of $\overline{p}$'s of the order of 10^{16}.

7 Antiproton production

There are 4 main steps from $\overline{p}$ production in high energy particle collisions, to the manufacture and storage of solid $\overline{H}$ (Fig. 3). In current systems, antiprotons are produced when protons of high enough energy (over 6 GeV) are fired into a target. These $\overline{p}$'s emerge with a wide variety of energies and a whole range of angles. This very broad beam of $\overline{p}$'s can be characterized by a very high temperature, of the order of 100's of MeV. The second step is to collect as wide a range of antiprotons as possible and to start concentrating them in velocity and angle while storing them in a first high energy storage ring. The third step is to accumulate them in a second ring while continuously "cooling" them until they all have the same velocity and angle. Finally, when the $\overline{p}$'s are cold enough, they can be decelerated to zero velocity and combined with positrons to form neutral antihydrogen. In this Section and the following three ones we examine the state-of-the-art in these techniques and the possibility of using them for large scale antimatter production, i.e., 10^{13} $\overline{p}$/s (10^{-6} g of $\overline{H}$ or 10^{18} $\overline{H}$ atoms per day).

The only antiproton factory in operation today is at CERN near Geneva. It produces 2×10^6 $\overline{p}$/s at the output of it's storage-cooling ring. By 1987, this

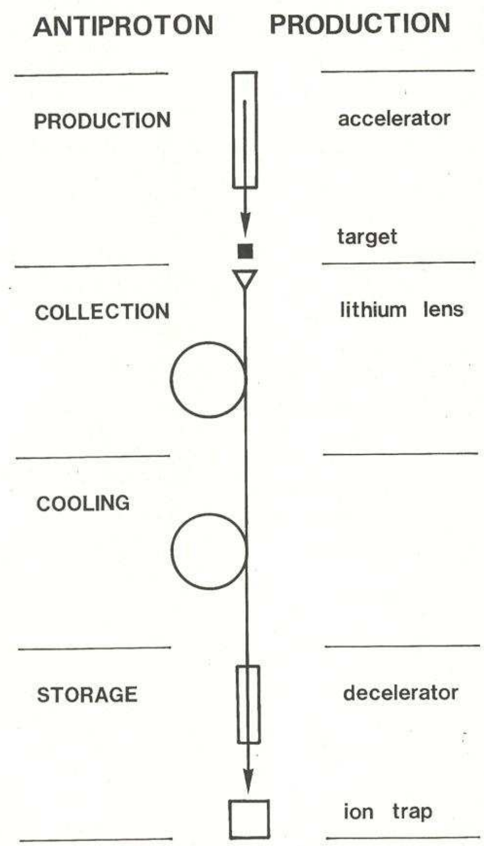

Figure 3: The four main steps of present-day technology antiproton production.

system will be upgraded to produce 2×10^7 $\overline{p}$/s [19]. At Fermilab, near Chicago, an antiproton source of the same intensity is under construction [20]. Antiprotons are also produced in the USSR [1] where there are plans for a system that will permit storage of 10^8 $\overline{p}$/s [21]. However, the most ambitious project is at Los Alamos where the $\overline{p}$ flux from the target is expected to be 100–200 times that of CERN [22].

The economic feasibility of an antiproton factory depends crucially on the accelerator system's transformation coefficient of electricity into antiproton rest mass. Since the number of antiprotons produced increases logarithmically with the collision energy, there is a broad optimum at 120 GeV, precisely the beam energy of the Fermilab $\overline{p}$ source. However, compared with a fixed target system, the use of a particle-particle collider [23] is a much more efficient means for high yield particle production. With this method the optimum corresponds to a (16+16) GeV collider. Such a collider could be built at Los Alamos where the construction of a high intensity 8 to 45 GeV synchrotron and possibly a future colliding beam facility [22, 24] are projected.

Colliding beams of heavy ions [25] may be an attractive alternative. Indeed, a heavy ion collider of the required luminosity might be easier to build than a proton collider, and in very high-energy-heavy ion-collisions, one expects an enhanced production of antiparticles such as antiprotons [26].

8 Antiproton collection

In fixed target systems, both at CERN and Fermilab, a Soviet designed lithium magnetic lens [27] is used to capture a wide spread of $\overline{p}$'s as they are produced at the target and to focus them on the aperture of the $\overline{p}$ collection channel (Fig. 3). A plasma lens [19, 28] could be used instead to improve the angular acceptance. However, it is more important to increase the momentum acceptance which is only 1 to 2% in present day systems. For that purpose, a linear debuncher between the production point and the first $\overline{p}$ storage ring could be used [29]. Together with other possible improvements, the overall collection efficiency could be as high as 0.05. To produce 10^{13} $\overline{p}$/s, assuming an electric power efficiency of 25%, the current of a 120 GeV beam would be 1 mA and the power load for the accelerator about 450 MW.

To collect the $\overline{p}$'s from a colliding beam source, there is an advantage in having a small asymmetry in the two beam energies, for example 14 and 18 GeV. The center of mass energy would still be very close to optimum but the $\overline{p}$'s produced at the threshold would go precisely in the direction of the fast beam, and with an energy equal to the difference of the beam energies [30]. Assuming again a collection efficiency of 0.05, the required luminosity for a proton-proton collider would be 6×10^{40} for each of the 8 interaction points as in Fig. 4. The total beam current for supplying 14 and 18 GeV protons to the collider is then 0.6 mA and the power load 50 MW. These numbers are quite close to the state-of-the-art. For example, the present 0.8 GeV Los Alamos accelerator normally runs with a current of up to 0.9 mA, and there is a proposal to accelerate 0.17 mA of that beam to 8 GeV and as much as 0.07 mA up to 45 GeV [22]. But building the desired collider will be a much more difficult task [25], unless a big $\overline{p}$ production enhancement in heavy ion collisions is found.

9 Antiproton cooling

Cooling aims at reducing the angular and energy spread of a beam circulating in a storage ring. There are two basic techniques: electron cooling which was pioneered in the Soviet Union [21, 31] and stochastic cooling which has been invented at CERN [32]. In many respects electron and stochastic cooling are complementary [33]. The efficiency of electron cooling is best for the cold and stochastic cooling for the hot beams. This suggests combining pre-cooling with stochastic and final cooling with electrons.

Stochastic cooling systems based on present techniques are capable of cooling as many as 10^8 to 10^{10} $\overline{p}$/s [32]. Even with 8 systems working in parallel this is short by 2 to 4 orders of magnitude of being able to produce 10^{13} $\overline{p}$/s. The only solution known at this time to go beyond this limit is to use multiple cooling rings. If each of these rings is fed by a different collection channel, the theoretical improvement in the overall cooling rate is $n \ln n$, about 23, for 10 rings working in parallel.

The main advantage of electron cooling is that it does not suffer any intrinsic particle number limitation [21, 33]. But, unlike stochastic cooling, electron cooling times are strong functions of the $\overline{p}$ beam momentum and $\overline{p}$ beam temperature. Furthermore, electron cooling has never been tested with more than 10^9 particles [33]. Nevertheless, if sufficient debunching and precooling can be achieved, electron cooling should be capable of handling a rate of 10^{12} $\overline{p}$/s or higher. This is why most cooling research in both the USA and the USSR has concentrated on electron cooling. A conceivable system would consist of three rings as in Fig. 4. Then, if a combination of debunching, stochastic pre-cooling and electron cooling could cool 10^{12} $\overline{p}$/s, our problem would be solved. This is by no means a simple

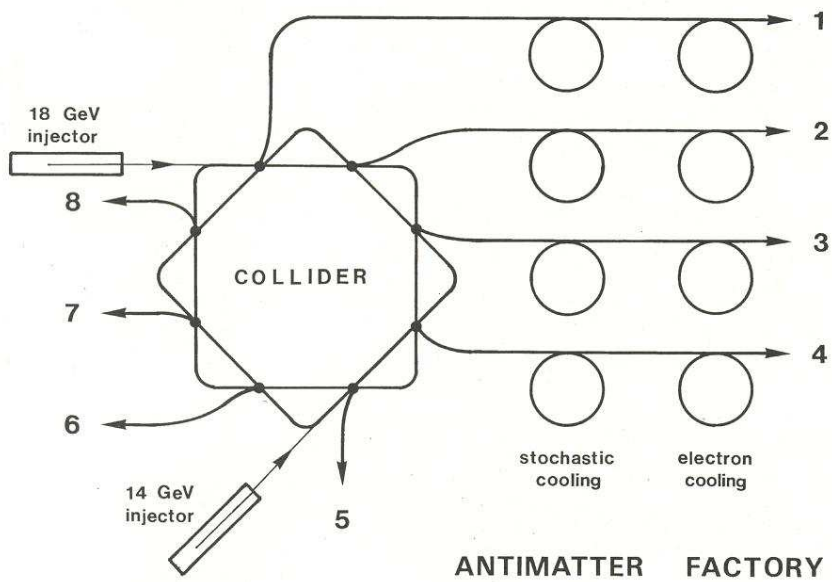

Figure 4: A possible design for a collider-based antiproton factory. Antiprotons are produced at the eight interaction points where the high energy ($\approx$16 GeV/nucleon) proton or heavy ion beams collide. The antiprotons are collected, cooled and processed into antihydrogen by eight systems working in parallel.

task, but there does not appear to be any fundamental obstacles.

10 Antiproton storage

The only antimatter storage technique proven today is that of storage rings [34, 35]. For practical applications, it is necessary to find more permanent means for storage, and for ease of handling, if possible in solid form. This problem has been studied extensively in the conceptual design of antimatter spacecraft propulsion systems [3]. Many different techniques are feasible in principle, but they still have to be tested experimentally.

In any event, the first thing is to decelerate the $\overline{p}$'s down to a few eV. For that purpose, the most promising method involves the use of a radio-frequency quadrupole [36] as a decelerator from 5 MeV (or more) down to approximately 100 keV, and to catch the $\overline{p}$'s in a ion trap in which they are cooled by resistive damping of image currents or by electron cooling [14]. In an ion trap (also called Penning trap) the density of stored $\overline{p}$'s can reach 10^{11} $\overline{p}$ cm^{-3} [37]. The lifetime of the $\overline{p}$'s is primarily limited by annihilation after capture by the residual gas atoms. Pressures lower than 10^{-15} Torr and liquid helium temperatures are required to keep the loss rate below 10^{-6} s^{-1}.

11 Antihydrogen production and storage

Much higher storage densities are possible if the antiprotons are combined with positrons to form neutral $\overline{H}$. Antihydrogen formation is quite difficult [38]. However, since positrons are much easier to produce and cool than $\overline{p}$'s, large scale $\overline{H}$ production is certainly feasible at a cost that would be marginal compared with the investment necessary for a full-scale $\overline{p}$ production plant.

Once neutral hydrogen has been formed, it has to be further slowed and cooled. Storage rings may be used to store $\overline{H}$, but for this purpose, cooling and subsequent manipulation, laser techniques are probably better. One method is called resonant radiation cooling and capture [39] which can also be used to create a trap for the atomic antihydrogen [40].

If atomic $\overline{H}$ is transformed into molecular $\overline{H}_2$, it can be cooled to very low temperatures where it will assume the low energy parahydrogen state. Since this molecule is diamagnetic, it can be directed to the storage container by hexapole-type magnetic field channels that have a zero field at the center. At temperatures below 14 K, the $\overline{H}_2$ molecules can then condense to form solid antihydrogen pellets which can be stored using either magnetic, electrostatic or laser levitation techniques [3].

For long term storage of solid $\overline{H}$ pellets, passive systems using permanent or superconducting magnets are probably the most promising. If some forces (due for example to the acceleration of a rocket) are acting on the pellet, the magnetic levitation system may be aided by an electrostatic field or a laser beam to balance them.

12 Discussion and conclusions

The physics of matter-antimatter interaction has been reviewed and the main conclusions can be summarized as follows:

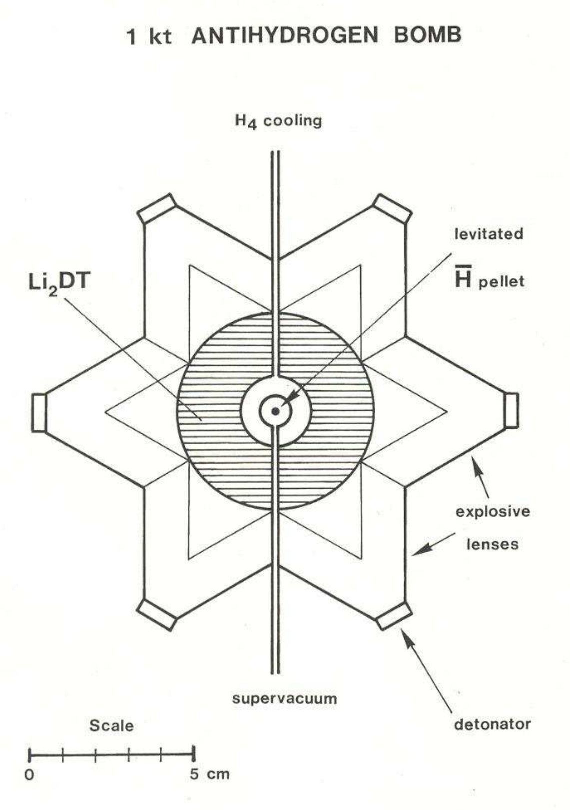

Figure 5: A possible design for a 1 kt antimatter bomb. One microgram of antihydrogen in a microcryostat is levitated at the center of a 100 g Li_2DT sphere. Implosion of the Li_2DT by means of chemical explosives brings the thermonuclear fuel into contact with the antihydrogen. The energy release by annihilation is fast enough to trigger an outgoing thermonuclear detonation wave which burns the Li_2DT. Depending on the amount of compression by the chemical explosives, the device operates as a 1 kt neutron bomb (ERW — Enhanced Radiation Warhead) or a 1 kt blast bomb (RRR – Reduced Residual radioactivity). In either case, the antimatter bomb will have very reduced radioactive fallout and electromagnetic pulse effects.

- Plasma heating by the charged particles produced in $\overline{p}$ annihilation with protons or nuclei is a rather inefficient process. However, if the fuel to be heated is slightly compressed ($\kappa = 30$), the energy from the low velocity particles (protons, recoiling nuclei) can be contained to give an energy deposition of about 15 to 35 MeV per annihilation in DT or Li_2DT.

- Annihilation in a hot matter-antimatter plasma is relatively slow: about 5 ns for a $H - \overline{H}$ plasma. However, if a small amount of antimatter is brought in contact with dense matter, annihilation in the boundary layer is quite fast. A pellet of $\overline{H}$ disappears in about 0.5 ns or respectively 0.2 ns when it comes in contact with a collapsing shell of compressed DT or Li_2DT. This very short duration energy release makes antimatter a good candidate as an energy source for pumping X-ray or gamma-ray lasers [4].

- The number of $\overline{p}$ annihilations required to start a thermonuclear burn wave in either DT or Li_2DT is found to be about $10^{21}/k^2$. Thus for $\kappa = 30$ (about the maximum compression factor that can be achieved with chemical explosives), $N = 10^{18}$.

The technologies for producing $\overline{p}$'s with high energy accelerator systems, and the means for manipulating and storing sizable amounts of $\overline{H}$ have been examined. With reference to the conceptual design of a 1 kt antihydrogen-triggered thermonuclear bomb shown in Fig. 5, and with the objective of designing an antimatter factory capable of producing the 10^{13} $\overline{p}$/s needed for manufacturing one such $\overline{H}$-bomb per day, the main results can be concluded as follows:

- Under ideal conditions such as highly efficient $\overline{p}$ collection and very small $\overline{p}$ losses throughout the plant, the production of 10^{13} $\overline{p}$/s requires either a fixed target system with a 1 mA, 120 GeV proton accelerator, or a (16+16) GeV colliding beam $\overline{p}$ source with a proton supply current of 0.6 mA. Assuming an AC power to beam power efficiency of 25%, the accelerator's electric power requirement is 500 MW in the fixed target and about 50 MW in the collider system. The energy needed to produce one $\overline{p}$ is thus of the order of 10^{-6} J, so that the production of 10^{16} $\overline{p}$'s for each antimatter triggered ICF pellet would require an energy investment of at least 10^4 MJ. It will therefore be very difficult to achieve energy break-even in power generating reactors using annihilation techniques. Therefore, civilian applications of antimatter for power production are very unlikely.

- If the expected enhancement of $\overline{p}$ production in high-energy heavy-ion collisions is demonstrated by experiment, a high luminosity heavy-ion collider would probably be the best source of $\overline{p}$'s. Compared with a fixed target $\overline{p}$ source, a collider can be designed to optimize conditions for $\overline{p}$ collection and cooling.

- The most difficult problem is the cooling of the very hot $\overline{p}$'s produced in high energy collisions to temperatures low enough so that they can be permanently stored in (relatively) simple systems, or combined with positrons to form antihydrogen. The state-of-the-art is short by 2 to 4 orders of magnitudes from being able to cool 10^{13} $\overline{p}$/s. However, possible improvements in stochastic and electron cooling will probably bridge the gap.

- As intense beams of cold low-energy positrons become available, $\overline{H}$ formation becomes easier. Small pellets of solid $\overline{H}$ can be levitated in a vacuum by a variety of magnetic, electric and laser techniques, and stored for very long periods if the vacuum is better than 10^{-15} Torr.

- If $\overline{p}$ cavitation in superfluid helium is found experimentally, formation of $\overline{H}$ would not be necessary for long term bulk storage of antimatter.

- The electromagnetic levitation of a 10^{-6} g $\overline{H}$ pellet within a 1 mm diameter microcryostat at the center of a large Li_2DT sphere such as in Fig. 5 is a tremendous challenge for materials microtechnology. However, if metastable states of $\overline{p}$'s in $Li-$, $Be-$ or possibly $C-DT$ compounds are discovered, much simpler designs could be considered.

Before concluding, we note that a plant of the size required to produce the antimatter needed for one thermonuclear bomb trigger a day (10^{-6}g of $\overline{H}$ or 10^{18} $\overline{H}$ atoms per day) could consist of several 10's of accelerators and storage rings, and could require as many as several large nuclear power plants to supply the electricity. However, considering the advances in technology since 1945, the relative complexity and cost of such a $\overline{p}$ factory are not out of proportion with those of a large uranium enrichment plant. Indeed, a study by the RAND Corporation gives a cost estimate of $500 to 1000 million for a prototype factory providing 10 to 100 micrograms, and $5 to 15 billion for a full production factory with an output of about 10 mg per year [4].

From the point of view of non-proliferation of nuclear weapons, the fact that antimatter-triggered thermonuclear weapons will have extremely reduced radioactive fallout, even for ground bursts, is an important consideration. Since such explosives may be advocated for "peaceful nuclear explosions," the current non-proliferation regime is being threatened by the growing spread of high energy accelerator technologies [41]. Moreover, from a strategic point of view, the possible advent of extremely compact and essentially clean nuclear weapons would further diffuse the distinction between low-yield nuclear weapons and conventional explosives. Finally, in the event of a comprehensive test ban treaty, antimatter would provide a means for triggering laboratory and small scale thermonuclear explosions in a yield range which cannot easily be covered by underground explosions or classical ICF systems [41].

References

[1] Yu. D. Prokoshkin: *Particles of antimatter*. Die Naturwissenschaften **59** (1972) 282–284. — N.A. Vlasov: *Annihilation as an energy process*. Sov. At. Energy **44** (1978) 40–45.

[2] H. Hora: Laser interactions and related plasma phenomena **3B** (1974) 833. — H. Hora: Laser plasmas and nuclear energy, Plenum Press, New York (1975) 85–86, 97.

[3] Special issue of the Journal of the British Interplanetary Society on antimatter propulsion. JBIS **35** (1982) 387–424. — R.L. Forward: *Making and storing antihydrogen for propulsion*, Workshop on the Design of a Low-Energy Antimatter Facility in the USA, University of Wisconsin, October 3–5 (1985).

[4] B.W. Augenstein: *Concepts, problems, and opportunities for use of annihilation energy. Prepared for the United States Air Force*, RAND Note N–2302–AF/RC, June (1985) 61 pp.

[5] L.Gray and T.E. Kalogeropoulos: *Possible bio-medical applications of antiprotons*. Rad. Res. **97** (1984) 246–252.

[6] A.N. Sullivan: *A measurement of the local energy deposition by antiprotons coming to rest in tissue-like material*. CERN Preprint TIS–RP/149/CF (22 April 1985). Phys. Med. Biol. **30** (1985) 1297–1303.

[7] E. Fermi and E. Teller: *The capture of negative mesotron in matter*. Phys. Rev. **72** (1947) 399–408.

[8] H.P. Duerr and E. Teller: *Interaction of antiprotons with nuclear fields*. Phys. Rev. **101** (1956) 494–495.

[9] S.D. Bloom, M.H. Johnson and E. Teller: *Absorption of K^- mesons in nuclear surfaces*. Phys. Rev. Lett. **3** (1969) 28–30.

[10] D.L. Morgan and V.W. Hugues: *Atomic processes involved in matter-antimatter annihilation*. Phys. Rev. **D2** (1970) 1389–1399. For E. Teller see page 1399.

[11] A. Sakharov: Collected scientific work, Marcel Dekker Inc., New York (1982).

[12] A. Gsponer and J.-P. Hurni, *The physics of antimatter induced fusion and thermonuclear explosions*. In G. Velarde and E. Minguez, eds., Proceedings of the 4th International Conference on Emerging Nuclear Energy Systems, Madrid, June 30/July 4, 1986 (World Scientific, Singapore, 1987) 166–169. e-print arXiv:physics/0507114 available in PDF format at http://arXiv.org/pdf/physics/0507114

[13] D.L. Morgan, V.W. Hughes: *Atom-antiatom interactions*. Phys. Rev. **A7** (1973) 1811–1825. — W. Kolos et al.: Hydrogen-antihydrogen interactions. Phys. Rev. **A11** (1975) 1792–1796.

[14] M.V. Hynes: *Physics with low temperature antiprotons*. Physics with antiprotons at LEAR in the ACOL era. Editions Frontières, Gif-sur-Yvette, France (1985) 657–664.

[15] R. Ahlrichs et al. : *Antiprotonic helium and lithium with one or two electrons*. Z. Phys. **A306** (1982) 297–300.

[16] M.R. Clover et al.: *Low energy antiproton-nucleus interactions*. Phys. Rev. **C26** (1982) 2138–2151.

[17] P.L. McGaughey et al.: *Low energy antiproton-nucleus annihilation radius selection using an active silicon detector/target*. Los Alamos preprint LA-UR-86-819 (1986).

[18] K.A. Brueckner and S. Jorna: *Laser-driven fusion.*. Rev. Mod. Phys. **46** (1974) 325–367. — G. Fraley et al.: *Thermonuclear burn characteristics of compressed DT (and Li_2DT) microspheres*. Phys. Fluids. **17** (1974) 474–489.

[19] E.J.N. Wilson, ed.: *Design study for an antiproton collector for the antiproton accumulator*. CERN Report 83-10 (1983).

[20] R.E. Shafer: *Overview of the Fermilab antiproton source.* Proc. of the 12th Intl. Conf. on High-Energy Accel. Fermilab, Batavia, IL (1984) 24–25.

[21] G.I. Budker and A.N. Skrinsky: *Electron cooling and new possibilities in elementary particle physics.* Sov. Phys. Usp. **21** (1978) 277–296.

[22] Los Alamos National Laboratory: *A proposal to extend the intensity frontier of nuclear and particle physics to 45 GeV (LAMPF II)*. LA-UR-84-3982 (1984). — F.R. Huson: *Consideration of energy and cost for a kaon and/or $\overline{p}$ factory*. in Proc. of the workshop on LAMPF II synchrotron). Los Alamos, Feb. 8–12, 1982. LA-9511-C(1982) — J. Simpson: *An antiproton source for LAMPF II*. Ibid 49–57.

[23] G. Chapline: *Antimatter breeders. J. of the Brit. Interpl. Soc.* **35** (1982) 423–424. — G. Chapline and R. Moir: *Some thoughts on the production of muons for fusion catalysis*. Report UCRL-93611 submitted to Journal of Fusion Energy (January 15, 1986).

[24] N.J. DiGiacomo: *Relativistic heavy ions at LAMPF II*. In Physics with LAMPF II. Los Alamos report LA-9789-P (1983) 419–423.

[25] G.R. Young: *Accelerator-colliders for relativistic heavy ions, or in search of luminosity*. In R.E. Mischke, ed., Interaction between particle and nuclear physics, AIP Conf. Proc. No. 123 (1984) 169–175.

[26] U. Heinz et al.: *Antinuclei - a signature for the quark-gluon plasma*. Z. Phys. **A318** (1984) 247–248. — T.A. DeGrand: *Are antibaryons a signal for a phase transition in ultrarelativistic nucleus-nucleus collisions?* Phys. Rev. **D30** (1984) 2001–2004.

[27] B.F. Bayanov et al.: *The investigation and the design development of lithium lenses with large operating lithium volume*. Proc of the 12th Intl. Conf. on High-Energy Accel., Fermilab, Batavia, IL (1984) 587–590. — G. Biallos et al.: *Power test of the Fermilab lens for antiprotons*. Ibid 591–593.

[28] B. Autin: *The CERN antiproton collector.* CERN accelerator school - Antiprotons for colliding beam facilities. CERN 84-15 (1984) 525-528.

[29] F.E. Mills: *Collecting antiprotons.* Physics with LAMPF II. Los Alamos report LA-9798-P (1983) 424–428.

[30] R.R. Wilson: *Slow target accelerator*. In: R. Donaldson, ed. Proc. of 1982 DPF study on elementary particle physics and future facilities, Snowmass, CO (1982) 329.

[31] H. Poth, ed: Proceedings of the Workshop on electron cooling and related applications-ECOOL 1984. KfK Report 3846, Karlsruhe (1985).

[32] D. Mohl: *Stochastic cooling for beginners*. CERN accelerator school – Antiprotons for colliding beam facilities. CERN 84-15 (1984) 97–124. —

D. Mohl, G. Petrucci, L. Thorndahl, S. van der Meer: *Physics and technique of stochastic cooling*. Phys.Rep. **58** (1980) 73–119.

[33] D. Mohl: *A comparison of stochastic and electron cooling*. CERN/PS/85-8(LEA). In Ref. 31, pp. 293–302.

[34] U. Gastaldi and R. Klapisch: Physics at LEAR with low energy cooled antiprotons. (Plenum Press, New York,1984).

[35] U. Gastaldi et al.: Physics in the ACOL era with low-energy cooled antiprotons, Editions Frontière, Gif-sur-Yvette, France, 1985.

[36] J.H. Billens et al.: *An RFQ as a particle decelerator*. In Ref. 35 (1985) 107–114.

[37] G. Gabrielse: *High-precision $\overline{p}$ mass comparison in a Penning trap*. In Ref. 35 (1985) 665–674. — W. Kells: *Remote antiproton sources.* IEEE Trans. on Nucl. Sci. **NS-32**, No. 5 (1985) 1770–1772.

[38] H.Herr et al.: *Production and experimentation with antihydrogen at LEAR*. In Ref. 34, p. 659–676. — A. Wolf et al.: *Electron cooling of low-energy antiprotons and production of fast antihydrogen atoms*. Proceedings of the Workshop on the Design of a Low-Energy Antimatter Facility in the USA, University of Wisconsin-Madison, October 3–5 (1985).

[39] J. Prodan et al.: *Stopping atoms with laser light*. Phys. Rev. Lett. **54** (1985) 992–995. — W. Ertmer et al.: *Laser manipulation of atomic beams*. Ibid (1985) 996–999. — J.J. Bollinger et al.: *Laser-cooled atomic frequency standard*. Ibid (1985) 1000–1003.

[40] V.S. Letokov et al.: *Cooling and capture of atoms and molecules by a resonant light field*. Sov. Phys. JETP **45** (1977) 698–705. — J.P. Gordon and A. Ashkin: *Motion of atoms in a radiation trap*. Phys. Rev. **A21** (1980) 1606–1617.

[41] A. Gsponer, B. Jasani, and S. Sahin: *Emerging nuclear energy systems and nuclear weapon proliferation*. Atomkernenergie · Kerntechnik (Independent Journal on Energy Systems and Radiation) **43** (1983) 169–174.