The physics of antimatter induced fusion and thermonuclear explosions

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Abstract

The possibility 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 $\kappa$ is the compression factor of the fuel to be ignited. We conclude that the financial and energy investments needed to produce such amounts of antiprotons would confine applications of antimatter triggered thermonuclear devices to the military domain.

1 Introduction

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

*Published 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. For the circumstances of the delivery of this paper, which was the first presentation at a scientific conference of the correct physical processes leading to the ignition of a large scale thermonuclear explosion using less than a few micrograms of antimatter as trigger, see Ref. [14]. See also Ref. [15]. Since this paper and its extended version, Ref. [10], have been published, many reports have confirmed their correctness, see, e.g., Refs. [16][17].
Other practical applications of antimatter are under consideration. For example, antimatter propulsion systems [3], space based power generators [4], directed energy weapons [4], cancer therapy [5]. Finally, both Edward Teller [6 7 8] and Andrei Sakharov [9], 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 [10].

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 [8]. 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 \(p\bar{p}\) annihilation process is as follows:

\[ p + \bar{p} \rightarrow 3 \pi^\pm + 4 \gamma, \]

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 \(p\bar{p}\) annihilation.

Antiprotons, antineutrons and positrons can combine to form antinuclei, antiamolecules. 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 [8]. As a consequence, storage of antiamolecules in a container made of matter is impossible in general. However, there may exist metastable states of antiprotons in normal matter [11].

3 Plasma heating with antiprotons

When a \(p\) 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: \( \frac{dE}{dx} = 0.52 \text{ MeV/cm in solid } H_2 \text{ or } DT \) 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 \( R = 1 \text{ cm} \) 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 \( \kappa \), \( \frac{dE}{dx} \) will then be multiplied by \( \kappa \), 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 \( \frac{dE}{dx} \). However, their thermonuclear ignition temperature is also higher. Finally, annihilation may take place with a nucleus.

When a \( \overline{\nu} \) 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

\[
dW = \nu \frac{dE}{dx} R + \epsilon, \quad (2)
\]

where \( \nu = 3 \) is the number of charged pions and \( \epsilon \) 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 \( \epsilon \) is approximately 12 MeV on the average, about half of the Fermi energy. With heavy nuclei there have been many theoretical speculations in the absence of measurements. The first of these was introduced by Duerr and Teller [7], who speculated that an antiproton would find a very strong (900 MeV) attractive potential when getting close to a nucleus. More recently [12], 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 [5]. 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:

\[
\epsilon \approx 6.4A^{2/3} \quad \text{[MeV]}, \quad (3)
\]

Hence, for \( \overline{p} \) annihilation in \( H_2 \), \( DT \) or \( Li_2DT \), \( \nu \) is always about 3 and \( \epsilon \) is approximately equal to 0, 12 or 22 MeV respectively.
Figure 1: Electron-positron and proton-antiproton annihilation reaction rates averaged over the Maxwell velocity distribution.

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 $\bar{n}$, is

$$\frac{dn}{dt} = -n\bar{n}\langle \sigma v \rangle,$$

(4)

where $\langle \sigma v \rangle$ is the annihilation reaction rate averaged over the Maxwell distribution.

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

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

(5)

If we assume $T = 20$ keV, $\langle \sigma v \rangle$ is approximately the same for both $e^+e^-$ and $p\bar{p}$ 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 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

\[
\frac{dN}{dS \, dt} = -\pi c \sqrt{\frac{kT}{2\pi mc^2}}. \tag{6}
\]

The \(e^+\) annihilation rate is thus \(\sqrt{m_p/m_e} \approx 43\) times the \(\bar{p}\) annihilation rate. However, since the \(H\) 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 \(H\)’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. To solve Eq. (6) one has to calculate the increase in the \(H\) plasma internal energy by the pions and other particles from \(\bar{p}\) annihilation in the surrounding DT:

\[
dW = -dN \frac{1}{2} \left( \nu \frac{dE}{dx} + \frac{\epsilon}{\lambda} \right) 4R \frac{N}{\pi} \frac{N_0}{N_0}, \tag{7}
\]

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

\[
T = T_1 \tanh^2(t/\tau_a) \quad \text{and} \quad N = N_0 \left( 1 - \tanh^2(t/\tau_a) \right). \tag{8}
\]

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.
Figure 2: In the configuration for a 1 kt antimatter bomb shown above, 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. 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 [13]. 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.
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.

In the spark model of thermonuclear ignition, 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 $\kappa$.

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

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

(9)

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

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

(10)

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. (9) and (10) 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 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
7 Discussion

The production of $10^{16}$ $\bar{p}$’s for each antimatter triggered ICF pellet would require an energy investment of at least $10^4$ MJ \[^{[10]}\]. It will therefore be very difficult to achieve energy break-even in power generating reactors using annihilation techniques. Moreover, the technologies for producing $\bar{p}$’s with high energy accelerator systems, and the means for manipulating and storing sizable amounts of $\bar{H}$ are extremely complicated. For instance, a plant of the size required to produce the antimatter needed for one thermonuclear bomb trigger a day ($10^{-6}$g of $\bar{H}$ or $10^{18}$ $\bar{H}$ 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 \[^{[10]}\]. 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 \[^{[4]}\]. As a consequence, civilian applications of antimatter for power production are very unlikely.

Directed energy weapons applications may include the triggering of thermonuclear plasma jets, and X-ray or gamma-ray laser pumping. In the event of a comprehensive test ban treaty, antimatter would provide a means for inducing laboratory and small scale thermonuclear explosions in a yield range which cannot easily be covered by underground explosions or classical ICF systems \[^{[13]}\]. Of course, many technical problems will have to be solved \[^{[10]}\]. In particular, the levitation of a frozen $\bar{H}$ pellet within a 1 mm diameter cryostat at the heart of a complex thermonuclear device is a tremendous challenge for materials microtechnology. However, if metastable states of $\bar{p}$’s in $Li-, Be-$ or possibly $C − DT$ compounds are discovered, much simpler designs could be considered.

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