

Plasmas Created in the Interaction of Antiprotons with Atomic and Ionized Hydrogen Isotopes. Suggested Fuels for Space Engines

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Abstract

The main objective of the present work is to investigate the properties of plasmas created by injecting a thermalized beam of antiprotons in two types of media. The first is hydrogen, deuterium, or tritium atoms localized in palladium crystals. The second medium is composed of protons, deuterons, or tritons localized in a magnetic cavity. Particularly, it is demonstrated that huge amounts of energy are released in both cases which could be used as fuels for space shuttle engines. A novel mathematical scheme is employed to calculate the energy yields in real space at different incident energies of the antiprotons.

Keywords

Antiprotons, Antiprotonic Hydrogens, Antiprotonic Plasma, Fuel for Space Engines, Plasmas in Molecular Crystals, Palladium as Host for Neutral Plasma, Antiprotons-Ionized Hydrogen Isotopes Plasma

1. Introduction

With the discovery of antiprotons (p) by Chamberlain *et al.* [1] at Fermilab in the fifties of the preceding century, the ultimate proof of possible formation of antiparticles in laboratory was rigorously confirmed. Consequently, Dirac's theory of holes [2] was acknowledged [3] as one of the fundamental theories of particle physics. The interest in the formation of cold antiprotons was demonstrated through the development of the "Low Energy Antiproton Ring (LEAR)" at CERN [4], in the early eighties of the preceding century which led in 1995 to the forma-

tion of the first antiatom in laboratory, namely the ANTIHYDROGEN by the ATHEN experiment [5] [6] (For more study about Antihydrogen see [7] [8] [9]). Other interesting experiments were performed after the development of the ATRAP machine at CERN ([10] [11] [12]) most of them seeking on the one hand, the production of large number of antihydrogen atoms, protoniums and protonium ions [13]. On the other hand, efforts were made to test the behavior of antimatter from the gravity point of view [14]. Recently, several applications of matter-antimatter interactions at low energy were explored ([15] [16] [17]).

Experimental investigations of plasmas involving antiprotons were carried out at the AEGIS, (for a review see [18] [19]). In this case nonneutral plasmas were studied in detail [20]. Formation of Matter-antimatter plasma, particularly high energetic electron-positron plasmas, was also proposed as plausible explanation for the mysterious radiation emitted from pulsars. The motive of the present work is the experimentally confirmed fact that matter-antimatter annihilation occurring by magnetically confined plasma releases much higher energy per unit mass comparative to any other source of propulsion [20] (For a comprehensive account on plasma theory and applications see [21]-[28]).

Our present work is concerned with two problems. The first is the formation of plasma through the interaction of antiprotons with highly populated hydrogen, deuterium or tritium atoms localized in a material host (e.g., palladium crystal). The second problem is to study plasmas formed by injecting a beam of antiprotons in a magnetic trap filled with protons, deuterons, or tritons.

The main objective of our investigations is to show that huge number of energies could be released from the plasmas created in both cases. Particularly, the employment of this plasma as fuel for engines of space shuttles is strongly emphasized.

The present paper falls in other three sections followed by a complete list of references mentioned in the text. The next section deals with the mathematical formalism of our problems. In Section 3 the results of our calculations are displayed and discussed. In Section 4 the main conclusions drawn from our investigations are presented. The paper concludes with the list of references mentioned in the text.

2. Mathematical Formalism

The present section is split into two parts, the first is devoted to the treatment of antiproton-atom plasmas and the second deals with the antiproton-nucleon plasmas.

2.1. Antiproton-Atom Plasmas

Consider a plasma which is composed of antiprotons (P^-), electrons (e^-) and hydrogen ions (H^+), (deuteron ions or triton ions, *i.e.*, D^+ or T^+ , respectively). For simplicity, it is assumed that the fluid of particles is forming an ideal gas.

Hence, the pressure of each stream is defined by $p_\alpha = \frac{3}{2}k_B T_\alpha n$, where p_α ; T_α ;

n_α are, respectively, pressure, the temperature, and density of the particle gas, whilst k_B is Boltzmann constant. The model is explained by the fluid equations.

The continuity equation for particles is given by.

$$\frac{\partial n_\alpha}{\partial t} + \frac{\partial}{\partial x}(n_\alpha u_\alpha) = 0, \quad (1)$$

The equation of motion for particle has the form.

$$\frac{\partial u_\alpha}{\partial t} + u_\alpha \frac{\partial u_\alpha}{\partial x} + \frac{1}{m_\alpha n_\alpha} \frac{\partial p_\alpha}{\partial x} + \frac{q_\alpha}{m_\alpha} \frac{\partial \phi}{\partial x} = 0, \quad (2)$$

where α stands for e^- ; P^- ; H^+ ; D^+ ; or T^+ .

Poisson's equation is expressed by

$$\frac{\partial^2 \phi}{\partial x^2} = \frac{e}{\epsilon} (n_{P^-} + n_e - n_i) \quad (3)$$

where m_α ; u_α ; and q_α denote, respectively, the mass, velocity and charge of the particle α in the stream. ϕ is the electrostatic potential and the index i refers to H^+ ; D^+ ; or T^+ . The fluid system of Equations (1)-(3) are normalized by the dimensionless variables $x \rightarrow \omega_i x / C_s$; $t \rightarrow \omega_i t / C_s$; $N = n/n_0$; $U_\alpha = u_\alpha / C_s$ and $\phi = e\phi / 2k_B T_e$; where ω_i is the plasma frequency of particle and n_0 is the equilibrium density, and $C_s = \sqrt{\frac{2k_B T_e}{m_i}}$ is the acoustic wave speed and T_e is the electron temperature respectively. Thus, the normalized system is described by the equations.

$$\frac{\partial N_\alpha}{\partial t} + \frac{\partial}{\partial x}(N_\alpha U_\alpha) = 0 \quad (4)$$

$$\frac{\partial U_\alpha}{\partial t} + U_\alpha \frac{\partial U_\alpha}{\partial x} + v_{\alpha 0} N_\alpha \frac{\partial N_\alpha}{\partial x} + v_{\alpha 1} \frac{\partial \Phi}{\partial x} = 0 \quad (5)$$

$$\frac{\partial^2 \Phi}{\partial x^2} = N_{P^-} + N_e - N_i$$

where $v_{\alpha 0} = \frac{3}{4} M_{i\alpha} \tau_{e\alpha}$, $v_{\alpha 1} = Q_\alpha M_{i0}$; $M_{i\alpha} = m_i / m_\alpha$, $\tau_{e\alpha} = T_\alpha / T_e$ and

$Q_\alpha = q_\alpha / e$ with $Q_{e,P^-} = -1$; and $Q_i = 1$. Stretching coordinates are defined by $\xi = \varepsilon^{1/2}(x - vt)$; and $\tau = \varepsilon^{3/2} vt$; and

$$N_\alpha = N_{\alpha 0} + \varepsilon N_{\alpha 1} + \varepsilon^2 N_{\alpha 2} + \dots, \quad U_\alpha = U_{\alpha 0} + \varepsilon U_{\alpha 1} + \varepsilon^2 U_{\alpha 2} + \dots \quad (6)$$

$$\text{and } \Phi = \varepsilon \Phi_1 + \varepsilon^2 \Phi_2 + \dots$$

$$N_{i0} = N_{P^-0} + N_{e0} \quad (7)$$

$$\frac{\partial \Phi_1}{\partial \tau} + 2A_1 \Phi_1 \frac{\partial \Phi_1}{\partial \xi} + B_1 \frac{\partial^3 \Phi_1}{\partial \xi^3} = 0 \quad (8)$$

and

$$h_{P^-0} + h_{e0} - h_{i0} = 0. \quad (9)$$

Hence, the solution of kdv Equation (8) and the first order perturbation of velocity and density of particle are given by

$$\begin{aligned}\Phi_1 &= \frac{3v}{2A_1} \operatorname{sech}^2\left(\sqrt{v/4B_1}Y\right) \\ U_{\alpha 1} &= \frac{3v_{\alpha 1}v}{2A_1}(v-U_{\alpha 0})\eta_{\alpha 0}\operatorname{sech}^2\left(\sqrt{v/4B_1}Y\right) \\ N_{\alpha 1} &= \frac{3v_{\alpha 1}v}{2A_1}N_{\alpha 0}\eta_{\alpha 0}\operatorname{sech}^2\left(\sqrt{v/4B_1}Y\right)\end{aligned}\quad (10)$$

where, $A_1 = \frac{h_{i2} - h_{p-2} - h_{e2}}{h_{i1} - h_{p-1} - h_{e1}}$, $B_1 = \frac{1}{h_{i1} - h_{pr-1} - h_{e1}}$, $h_{\alpha 1} = 2v\eta_{\alpha 0}(v - U_{\alpha 0})h_{\alpha 0}$,

$$h_{\alpha 2} = \frac{v_{\alpha 1}}{2}\eta_{\alpha 0}^2 h_{\alpha 0}\left(3(v - U_{\alpha 0})^2 - v_{\alpha 0}\right), \quad h_{\alpha 0} = \frac{v_{\alpha 1}N_{\alpha 0}}{(v - U_{\alpha 0})^2 - v_{\alpha 0}N_{\alpha 0}^2},$$

$$\eta_{\alpha 0} = \frac{1}{(v - U_{\alpha 0})^2 - v_{\alpha 0}}$$
 and $Y = \xi - v\tau$. The normalized plasma kinetic energy

of zero and first perturbations for velocities and densities is.

$$\begin{aligned}KE &= \frac{1}{2}\sum_{\alpha}(N_{\alpha 0} + N_{\alpha 1})(U_{\alpha 0} + U_{\alpha 1})^2 \\ KE &= \frac{1}{2}\sum_{\alpha}m_{\alpha}(n_{\alpha 0} + n_{\alpha 1})(u_{\alpha 0} + u_{\alpha 1})^2\end{aligned}$$

2.2. Antiproton-Nucleon Plasma

Consider a system of fluid plasma consisting of two kinds of oppositely charged particles, namely negatively charged antiprotons (P^-) and positively charged Protons (P), Deuterons (D) or Tritons (T). Furthermore, assume that all plasmas are ideal gases. Consequently, the pressure of each plasma is calculated by

$p_{\alpha} = \frac{3}{2}k_B T_{\alpha} n_{\alpha}$, where p_{α} , T_{α} , and n_{α} stand, respectively, for the pressure, temperature, and density of particle stream, whilst k_B is Boltzmann constant. The model is explained by the following system of equations.

The continuity equation

$$\frac{\partial n_{\alpha}}{\partial t} + \frac{\partial}{\partial x}(n_{\alpha}u_{\alpha}) = 0, \quad (13)$$

the equation of motion

$$\frac{\partial u_{\alpha}}{\partial t} + u_{\alpha} \frac{\partial u_{\alpha}}{\partial x} + \frac{1}{m_{\alpha}n_{\alpha}} \frac{\partial p_{\alpha}}{\partial x} + \frac{q_{\alpha}}{m_{\alpha}} \frac{\partial \phi}{\partial x} = 0, \quad (14)$$

with $\alpha = P^-, P, D, T$ and

Poisson's equation

$$\frac{\partial^2 \phi}{\partial x^2} = \frac{e}{\epsilon}(n_{P^-} - n_i) \quad (15)$$

where m_{α} , u_{α} , and q_{α} are the mass, velocity, and charge of the particle α . ϕ is the electrostatic potential and the index i refers to P, D, or T.

The Plasma system of Equations (1)-(3) are normalized by the dimensionless variables $x \rightarrow \omega_i x / C_s$, $t \rightarrow \omega_i t / C_s$, $N = n/n_0$, $U_{\alpha} = u_{\alpha} / C_s$ and $\phi = e\phi / 2k_B T_e$, where ω_i is the plasma frequency of the particle i and n_0 is the

equilibrium density, and $C_s = \sqrt{\frac{2k_B T_e}{m_i}}$ is the acoustic wave speed and T_e is the electron temperature respectively. Thus, the normalized system is described by.

$$\begin{aligned} \frac{\partial N_\alpha}{\partial t} + \frac{\partial}{\partial x}(N_\alpha U_\alpha) &= 0 \\ \frac{\partial U_\alpha}{\partial t} + U_\alpha \frac{\partial U_\alpha}{\partial x} + v_{\alpha 0} N_\alpha^{-1} \frac{\partial N_\alpha}{\partial x} + v_{\alpha 1} \frac{\partial \Phi}{\partial x} &= 0 \\ \frac{\partial^2 \Phi}{\partial x^2} &= N_{p^-} - N_i \end{aligned} \tag{16}$$

where $v_{\alpha 0} = \frac{3}{4} M_{i\alpha} \tau_{e\alpha}$, $v_{\alpha 1} = Q_\alpha M_{i0}$; $M_{i\alpha} = m_i/m_\alpha$, $\tau_{e\alpha} = T_\alpha/T_e$ and $Q_\alpha = q_\alpha/e$ with $Q_{e,p^-} = -1$, and $Q_i = 1$. The stretching coordinates are defined by.

$$\xi = \varepsilon^{1/2} (x - vt),$$

and

$$\tau = \varepsilon^{3/2} vt,$$

and

$$\begin{aligned} N_\alpha &= N_{\alpha 0} + \varepsilon N_{\alpha 1} + \varepsilon^2 N_{\alpha 2} + \dots, \quad U_\alpha = U_{\alpha 0} + \varepsilon U_{\alpha 1} + \varepsilon^2 U_{\alpha 2} + \dots \\ \text{and } \Phi &= \varepsilon \Phi_1 + \varepsilon^2 \Phi_2 + \dots \end{aligned}$$

$$N_{i0} = N_{p^-0}$$

$$\frac{\partial \Phi_1}{\partial \tau} + 2A_1 \Phi_1 \frac{\partial \Phi_1}{\partial \xi} + B_1 \frac{\partial^3 \Phi_1}{\partial \xi^3} = 0 \tag{20}$$

and

$$h_{p-0} - h_{i0} = 0. \tag{21}$$

Hence, the solution of kdv Equation (8) and the first order perturbation of the velocity and density of the particle are given by

$$\begin{aligned} \Phi_1 &= \frac{3v}{2A_1} \text{sech}^2(\sqrt{v/4B_1} Y) \\ U_{\alpha 1} &= \frac{3v_{\alpha 1} v}{2A_1} (v - U_{\alpha 0}) \eta_{\alpha 0} \text{sech}^2(\sqrt{v/4B_1} Y) \\ N_{\alpha 1} &= \frac{3v_{\alpha 1} v}{2A_1} N_{\alpha 0} \eta_{\alpha 0} \text{sech}^2(\sqrt{v/4B_1} Y) \end{aligned} \tag{22}$$

$$A_1 = \frac{h_{i2} - h_{p-2}}{h_{i1} - h_{p-1}}, B_1 = \frac{1}{h_{i1} - h_{p-1}}, h_{\alpha 1} = 2v\eta_{\alpha 0} (v - U_{\alpha 0}) h_{\alpha 0}.$$

$$h_{\alpha 2} = \frac{v_{\alpha 1}}{2} \eta_{\alpha 0}^2 h_{\alpha 0} \left(3(v - U_{\alpha 0})^2 - v_{\alpha 0} \right), \quad h_{\alpha 0} = \frac{v_{\alpha 1} N_{\alpha 0}}{(v - U_{\alpha 0})^2 - v_{\alpha 0} N_{\alpha 0}^2},$$

$$\eta_{\alpha 0} = \frac{1}{(v - U_{\alpha 0})^2 - v_{\alpha 0}} \quad \text{and} \quad Y = \xi - v\tau.$$

The normalized kinetic energies of the plasma corresponding to the zero and

first order perturbations of the velocities and densities are determined by

$$KE = \frac{1}{2} \sum_{\alpha} (N_{\alpha 0} + N_{\alpha 1}) (U_{\alpha 0} + U_{\alpha 1})^2$$

$$KE = \frac{1}{2} \sum_{\alpha} m_{\alpha} (n_{\alpha 0} + n_{\alpha 1}) (u_{\alpha 0} + u_{\alpha 1})^2$$

3. Results and Discussion

As shown in tables. The following values of particle masses have been employed in the present work.

Proton mass $m_p = 1.6726231 \times 10^{27}$ kg, Deuteron mass $m_D = 3.3476 \times 10^{-27}$ kg; and triton mass $m_T = 5.0225 \times 10^{-27}$ kg, $M_{\bar{p}} = M_p = 1.0073 \times 10^{-6}$ g, $M_D = 2.0160 \times 10^{-6}$ g, $M_T = 3.0246 \times 10^{-6}$ g, $M_{e^-} = 5.4858 \times 10^{-2}$ g, $M_{pp\bar{e}^-} = 3.02245 \times 10^{-6}$ g; $M_{DPe^-} = 5.03985 \times 10^{-6}$ g; $M_{Tpe^-} = 7.05705 \times 10^{-6}$ g.

Normalized kinetic energy (KE) against Y for electrons, antiprotons and hydrogen, deuterium, or tritium are demonstrated in **Figures 1-3** and for antiprotons and protons, deuterons, and tritons are displayed in **Figures 4-6**.

Data Availability Statements

The data of the calculated energy that support the findings of this study are derivative in at <https://doi.org/10.1016/j.physleta.2014.10.006>, reference number [22] [23].

Table 1. Stretching velocity for protons, deuterons, or tritons with electrons and antiprotons for different velocities of antiprotons, $u_e = C_s$, $u_i = 9 \times 10^7 C_s$; $N_e = 1$, $N_p = 1$, and $N_i = 2$.

u_{Pi}	$0.9C_s$	$0.09C_s$	$0.009C_s$
v_H	1.2243118163856073	1.181085869585997	0.2761483671130386
v_D	1.2243118376157038	1.1834150339194047	0.33189855601735063
v_T	1.2243118459019127	1.1841406167744444	0.35936943838330293

Table 2. Frame stretching velocity for protons, deuterons, or tritons with electrons and for different velocities of antiprotons $u_i = 9 \times 10^7 C_s$; $N_p = 1$; and $N_i = 1$.

u_{Pi}	$0.9C_s$	$0.09C_s$	$0.009C_s$
v_H	1.2243118163856073	1.181085869585997	0.2761483671130386
v_D	1.2243118376157038	1.1834150339194047	0.33189855601735063
v_T	1.2243118459019127	1.1841406167744444	0.35936943838330293

Table 3. The non-normalized kinetic energy KE (J) of Plasma in Palladium for $n_0 = 6.0221367 \times 110^{23}$ mol⁻¹; $\epsilon = 13.7$; $u_i = 9 \times 10^7 C_s$; $u_e = C_s$, (H ; D ; or T , with P ; e) $Y = 0$ at T_e (K) = 273.

u_P	KE_H	KE_D	KE_T
$0.9C_s$	3.043700	3.042580	3.042210
$0.09C_s$	13.571500	13.92480	14.04160
$0.009C_s$	0.000672722	0.00146563	0.00220382

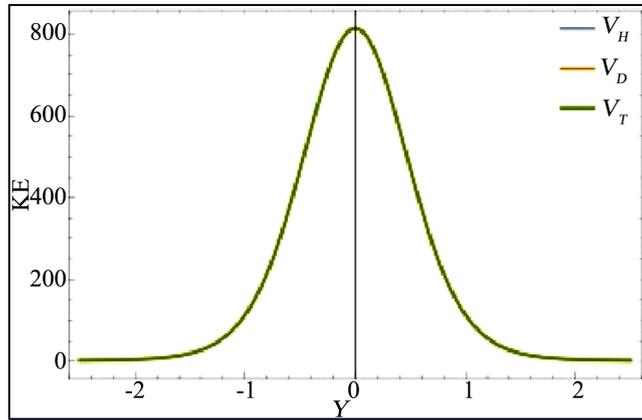


Figure 1. $u_p = 0.9 C_s$; $P = 1487.2$.

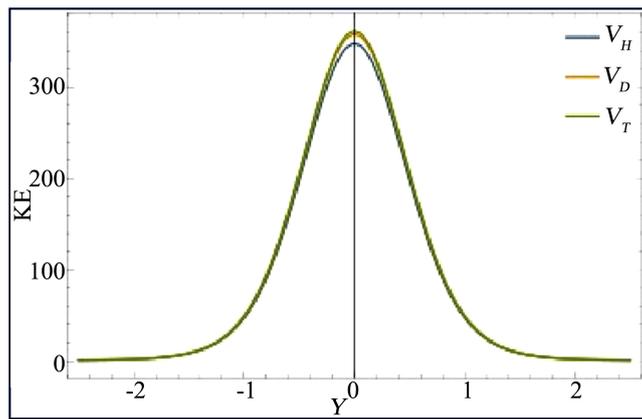


Figure 2. $u_p = 0.09 C_s$; $P = 14.872$.

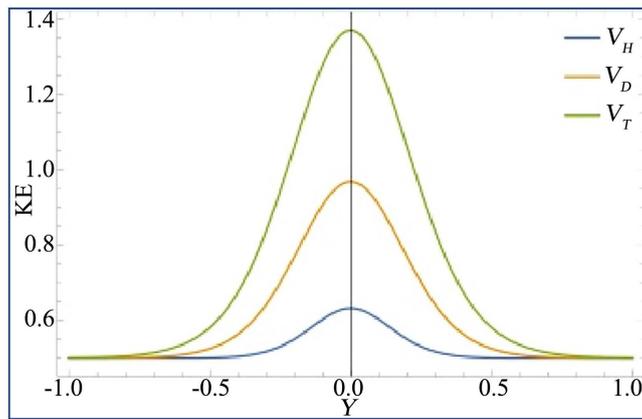


Figure 3. $u_p = 0.009 C_s$; $P = 0.14872$.

Table 4. For (P ; D ; or T , with P) $Y = 0$.

u_p	KE_P	KE_D	KE_T
$0.9 C_s$	1.02086×10^6	1.49712×10^6	1.75179×10^6
$0.09 C_s$	11.4938	1.6.6024	1.9.3171
$0.009 C_s$	0.000249961	0.000333362	0.000376228

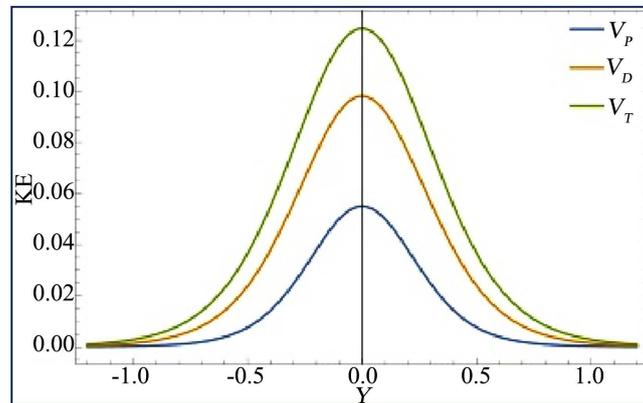


Figure 6. $u_p = 0.009 C_s$; $P = 0.14872$.

4. Conclusion

The one-dimensional hydrodynamic model of linear and nonlinear analyses in the term of electron-positron and proton-antiproton are studied. The linear analyses show a positive root that indicates ion-acoustic waves in the system and the possibility of existing soliton waves. Also, we obtain the calculations of the nonlinear analysis of the deformed kdv equation and the energy released of the formed plasma. The results, see **Tables 1-5** and **Figures 1-6**, show that the lifetime of formed plasma increases inside the palladium crystal 13.7 times concerning the free space. We have the same energy of formed plasma in the case of free space and palladium crystal. The renormalized example study assumes that when the velocity of the antiproton is around the ion-acoustic wave the released energy of the plasma could be reached to 1.15723×10^6 J/mole. On the other hand, if the velocity of the antiproton decreases, the total energy of the plasma system decreases. This result supports very much the conclusion that we suggested model for obtaining huge amount of energy by constructing a plasma state between thermalized hydrogen and antihydrogen in molecular crystals with approximate velocity less than the velocity of ion acoustic wave of the system. This energy could find interesting application in cold fusion and building up engines for space shuttles.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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