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The Typical Number of Antiprotons Necessary to Heat the Hot Spot in the D-T Fuel Doped with U

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Fast ignition scenario with heating the hot spot by products of annihilation of antiprotons in the D-T fuel doped with U^{238} is considered. It is shown that in this scenario the hot spot is being heated effectively only by the fission fragments arising due to annihilation of the antiprotons on the nuclei of uranium. The presented model predicts that fast ignition can be provided by injection of (1.3 to 4.4) x 10^{15} antiprotons into the D-T fuel compressed to the density of about 200 g/cm^3 and containing one nucleus of U^{238} per about one thousand nuclei of hydrogen isotopes.

Keywords: nuclear pulse propulsion, antimatter, fast ignition

1. Introduction

There are several proposals to use the annihilation of antiprotons for ignition of thermonuclear microexplosions and initiation of fission and fusion – fission microexplosions (see, e.g., Refs. [1-10]). The space propulsion is the main discussed area of applications of such scenarios, although some other applications may also be possible and expedient [1-10].

In Ref. [2] the use of the annihilation of antiprotons to heat the compressed thermonuclear fuel was proposed. According to Ref. [2], the antiprotons should annihilate on the nuclei of the fuel. Later, the use of annihilation of antiprotons on the heavy nuclei was also discussed [8-10]. The advantage of this reaction is that the ranges of some of its products in the fuel are rather short [8-10]. This enables the realization of the fast ignition of microexplosions [8-10].

Let us estimate the typical number $N_{\bar{p}}$ of antiprotons necessary for fast ignition with heating the hot spot by products of annihilation of antiprotons on U^{238} nuclei immersed into the D-T fuel. Such scenarios were proposed in Ref. [10], where the initial estimate of $N_{\bar{p}}$ was also presented. The necessity of the new estimate of this value results mainly from the following. The estimate presented in Ref. [10] did not take into account the real average numbers, usually called yields, and the kinetic energies of light nuclei arising due to annihilation of antiproton on the uranium nucleus. Comparison of the probabilities of annihilation of antiprotons on the nuclei of uranium and hydrogen isotopes was practically based on the estimates of the cross-sections for capture of antiprotons by atoms with ejection of electrons from hydrogen atom and the outer electron shell of the uranium atom. However, compression of the fuel to the density of the order of 100 g/cm^3 will result in the total ionization of hydrogen isotopes and the outer electron shell of uranium. When estimating the radiative losses related to uranium doping, only bremsstrahlung was taken into account, while in many situations the bound-bound transitions bring the important contribution into the radiative losses of the plasma containing the ions of the heavy element(s) [11].

2. The Typical Necessary Number of Fissions of the Uranium Nuclei due to Annihilation of Antiprotons

When estimating the energy E_{ign} necessary for heating the hot spot and other values describing the fast ignition scenario, let us assume that the fuel is compressed to the density

$$\rho = 200 \text{ g/cm}^3 \quad (1)$$

and the density n_D of deuterons equals the density n_T of tritons (for the sake of brevity, in this paper the term "density" is used to describe both the mass of unit volume and the number of particles in unit volume). According to these conditions and the model presented in Ref. [12], for the "clean" fuel, containing no uranium, the optimum value of E_{ign} is given by

$$E_{ign} \approx 38.8 \text{ kJ} \quad (2)$$

and the optimum radius r_{opt} of the hot spot is about 30.6 μm. In this paper the results of some of the intermediate calculations and, when possible, the experimental data are presented with three significant figures even if their relative accuracy is about 10 % or worse. The use of one extra significant figure corresponds to recommendations of Ref. [13] (pp. 19 and 23) and prevents arising the important round-off errors in the boundaries of $N_{\bar{p}}$ and some other values.

It is easy to show that in the situation under consideration practically the whole contribution of annihilation into heating the hot spot is brought by the fission fragments arising due to annihilation of antiprotons on the uranium nuclei.

The total kinetic energy E_{fr} of both fragments arising due to U^{238} nucleus fission caused by annihilation of slow antiproton is about 158 ± 26 MeV [14] (the necessity to use rather slow antiprotons for heating the hot spot is explained in Section 3). To estimate the typical range R_{fr}^{typ} of the fission fragment in the compressed fuel, let us assume that the atomic mass and the initial kinetic energy of the fragment are about 110 and 80 MeV, respectively, while its ionization stage z_{fr} is about 10 or greater. Using the model presented in Ref. [15] and Eq. (1), we obtain, for example, that in the "clean" fuel at the electron temperature $T_e = 12$ keV, $R_{fr}^{typ}(z_{fr}=10) \approx 0.92\,\text{g/cm}^2$, $R_{fr}^{typ}(z_{fr}=15) \approx 0.45\,\text{g/cm}^2$, $R_{fr}^{typ}(z_{fr}=20) \approx 0.27\,\text{g/cm}^2$, while at $T_e = 1$ keV, even $R_{fr}^{typ}(z_{fr}=10)$ is only about 0.094 g/cm^2. All of the aforementioned values of R_{fr}^{typ} seem to be sufficiently short. Note that the model from Ref. [15] and Eq. (1) yield that in the "clean" fuel at T_e of 1 and 12 keV the ranges R_α of the α-particle with the initial kinetic energy of 3.5 MeV are about 0.041 and 0.67 g/cm^2, respectively. Note also that the real typical values of z_{fr} are probably greater than 10 even at $T_e \approx 1$ keV. For example, the formula from Ref. [10] (p. 1106) yields that at T_e of 1 and 12 keV the uranium ionization stages z_U are about 23 and 71, respectively. Thus, the real values of R_{fr}^{typ} may be less than R_α.

The yields of light nuclei arising due to annihilation of slow antiproton on a nucleus that is not a product of the recent annihilation of other antiproton(s) on a more heavy nucleus are rather low [14,16-18]. The yield of protons arising due to annihilation of slow antiproton on nucleus of U^{238} is not greater than about 1.7 [16-18]. The contribution of the protons with the kinetic energies ε_k greater than 40 MeV into heating the hot spot is negligible due to both long ranges of these protons in the fuel (see, e.g., Refs. [15,19,20]) and their low yield (see Refs. [16-18]). Note that in the situation under consideration the yield of protons with $\varepsilon_k = 6$ to 18 MeV is about 0.8, the yield of deuterons with $\varepsilon_k = 8$ to 24 MeV is about 0.3, the yield of tritons with $\varepsilon_k = 11$ to 29 MeV is about 0.2, and the yields of He^3 and He^4 with $\varepsilon_k = 36$ to 70 MeV are about 0.03 and 0.06, respectively [16] (see also Refs. [17,18]). These particles will bring some contribution into heating the hot spot. However, this contribution will probably not be greater than about 10 % of that of the fission fragments. Heating any region of the fuel by other light nuclei is negligible due to their low yields (see Refs. [16,17]). Heating the hot spot by charged pions, high-energy photons arising due to decay of neutral pions, and neutrons is negligible due to the low cross-sections for their interactions with the particles of the fuel (see also Refs. [2,8-10] and Section 4).

Thus, condition (2) yields that if an increase in E_{ign} due to doping the fuel is negligible, the number N_1 of the uranium nuclei that undergo fission due to annihilation of antiprotons should be about (1.32 to 1.83) x 10^{15}. Here it is assumed that "indirect" heating the hot spot due to fission of uranium nuclei by the arising neutrons and pions is negligible. The validity of this assumption is shown in Section 4.

Note that the use of annihilation of antiprotons on the fissionable nuclei to heat the plasma by the fission fragments was proposed in Ref. [1], where the value $E_{fr} \approx 160$ MeV was mentioned. Note also that when analyzing the attainable efficiency of the use of annihilation of antiprotons for heating the converter(s) of the indirectly driven target, only heating by the fission fragments was taken into account [6].

3. The Factors Determining the Probability of Annihilation of Antiproton on the Uranium Nucleus

Let us denote the density of the uranium nuclei in the fuel as n_U and estimate the ratio $f_U = n_U/(n_U + n_D + n_T)$ that provides fast ignition at the minimum $N_{\bar{p}}$. The choice of f_U should provide both the sufficiently high probability p_U of annihilation of antiproton on the uranium nucleus and the sufficiently low radiative losses [10].

3.1 The Radiative Losses and f_U

In the fast ignition scenario with doping or contamination of the fuel by the heavy element the radiative losses per one nucleus of this element will be rather high. For example, if compression of the D-T fuel contaminated with gold corresponds to Eq. (1) and $n_D = n_T$, the ratio $f_{Au} = n_{Au}/(n_{Au} + n_D + n_T)$, where n_{Au} is the density of the gold nuclei, should not be greater than about 2 x 10^{-3} [19]. If this condition is satisfied, E_{ign} is close to the right-hand side of Eq. (2), while an increase in f_{Au} above 2 x 10^{-3} results in the very strong increase in E_{ign} [19].

The exact calculations of the average radiative losses per one heavy element ion immersed into the high-density plasma are very complicated (the main difficulties are related to emission of photons due to the bound-bound transitions and, in some situations, reabsorption of photons) [11]. Therefore, when estimating f_U, it is expedient to use the requirement on f_{Au} from Ref. [19], the fact that the ratio of the atomic numbers Z of U and Au, namely, 92/79 ≈ 1.16, is rather close to unity, and the data from Ref. [11] on the dependence of the radiative losses on Z.

If the optical thickness of the plasma is not too high, the total rate of the radiative losses can be described within the approximation of the optically thin plasma even if reabsorption has effect on the shapes of the spectral lines [11]. If such a plasma consists of ions of one element and electrons, the rate of the radiative losses per one ion and one electron is being described by the parameter Q [11]. According to definition of this parameter, the energy dE_{rad} of radiation emitted from the volume dV during the time dt equals Qn_en_idVdt, where n_e and n_i are the densities of electrons and ions, respectively [11]. If the plasma consists of ions of several elements, the approximation of the optically thin plasma yields $dE_{rad} = n_e dVdt \sum_k Q_k n_{i(k)}$, where Q_k is the parameter Q corresponding to the k-th element, $n_{i(k)}$ is the density of the ions of this element.

According to fig. 5 of Ref. [11], for the fixed T_e from the range $0.1 \text{ keV} \le T_e \le 100 \text{ keV}$ the maximum of the ratio $Q(\text{Nd})/Q(\text{Cu})$, or, in other words, of the ratio $Q(Z = 60)/Q(Z = 29)$, is about 35 (this maximum corresponds to $T_e \approx 2.5$ keV, n_e is not mentioned). Using this and the fact that $35 \approx (60/29)^{4.9}$, let us extrapolate the dependence $\max[Q(Z = Z_2)/Q(Z = Z_1)]$ in the range $29 \le Z_{1,2} \le 92$ or at least $79 \le Z_{1,2} \le 92$ for any n_e by $(Z_2/Z_1)^{4.9}$. This extrapolation yields

$$\max[Q(Z = 92)/Q(Z = 79)] \approx 2.1 \quad (3)$$

Note that at $T_e \ge 1$ keV, the dependence $Q(n_e)$ seems to be rather weak. For example, fig. 2 of Ref. [11] yields that for iron at $T_e = 1$ keV, the ratio $Q(n_e = 10^{14} \text{ cm}^{-3})/Q(n_e = 10^{21} \text{ cm}^{-3})$ is about 2, at $T_e \ge 3$ keV, this ratio is in the range from 1 to about 1.04.

Eq. (3) and the requirement on f_{Au} from Ref. [19] allow us to assume that

$$f_U \approx 10^{-3} \quad (4)$$

and Eq. (1) correspond to E_{ign} of about the right-hand side of Eq. (2) or, in other words, to the negligible increase in E_{ign} due to doping the fuel.

To check the compatibility of Eq. (4) with the requirements on N_1, let us assume that the hot spot is a cylinder with the radius r_{opt} and the length $l \approx 60$ μm (see Ref. [12]) and is heated due to annihilation of antiprotons inside it. The number N_{fuel} of the thermonuclear fuel atoms in this cylinder is about 8.50 x 10^{18}. Thus,

$$N_1/N_{fuel} \approx (1.6 \text{ to } 2.2) \text{ x } 10^{-4} \quad (5)$$

This equation is compatible with Eq. (4).

3.2 Capture of Antiprotons and Annihilation in Flight

Despite of the low f_U corresponding to Eq. (4), it is possible to provide a rather high p_U. The main reason is that at the electron temperatures $T_e \le 10$ to 17.4 keV, corresponding to heating the hot spot [12,15,19,20], almost all of the uranium nuclei have at least one bound electron (this can be shown using the Saha formula; see also the aforementioned values of z_U and Ref. [10] (p. 1106)). Therefore, they can capture the antiproton with ejection of the electron. The antiproton bound with the uranium nuclei will annihilate on it (see also Refs. [14,16,18,21,22]).

Let us estimate the cross-section for capture of the antiproton with ejection of the electron from the hydrogen-like ion of the element with

$$Z \ge 2 \quad (6)$$

in the situation when the antiproton kinetic energy obeys the condition

$$\varepsilon_{\bar{p}} \le Z^2 \times 13.6 \,\text{eV} \quad (7)$$

and before the collision the ion is in the principal state.

If the impact parameter is not greater than a_B/Z, where $a_B \approx 5.29 \text{ x } 10^{-9}$ cm is the Bohr radius, the bound electron will be strongly influenced by the antiproton (conditions (6,7) are imposed to provide the low probability of ionization of the ion without capture of the antiproton and a relatively long time of interaction of the antiproton with the ion). Therefore, it seems that in such a case the probability of capture of the antiproton with ejection of the electron is about unity (see also Ref. [23] (Chapter VI, paragraph 6), where a similar estimate is presented). Thus,

$$\sigma^c_{H-like}(Z \geq 2, \varepsilon_{\bar{p}} \leq Z^2 \times 13.6\,\text{eV}) \approx \pi a_B^2 / Z^2 \quad (8)$$

Substituting Z = 92 into Eq. (8), we obtain

$$\sigma^c_{H-like}(Z = 92, \varepsilon_{\bar{p}} \leq 115\,\text{keV}) \approx 1.0 \times 10^{-20}\,\text{cm}^2 \quad (9)$$

Eqs. (1,4,9) correspond to the capture of the antiproton on the typical path of about 20 μm . Since this path is about $l/3$, it is sufficiently short.

Some of the antiprotons will annihilate on the fission fragments. For the conservative estimate of $N_{\bar{p}}$, let us assume that such annihilation is equivalent to the loss of the antiproton due to the low efficiency of transfer of the kinetic energies of its products to the fuel. In principle, annihilation of the antiproton on the highly exicited fission fragment or other nucleus that arose due to the recent annihilation of another antiproton on a more heavy nucleus may result in the so-called multifragmentation, i. e., the explosive decay of the nucleus into the relatively small fragments, but this problem requires the additional studies [24]. If the multifragmentation occurs, the ranges of at least some of the fragments in the compressed fuel would probably be rather short.

The cross-section for the capture of the antiproton by the ion of the fission fragment with ejection of the electron from the K-shell seems to be about the cross-section for the capture of the antiproton by the uranium ion with ejection of the electron from the L-shell or less. At the end of heating the hot spot almost all of the fission fragments will be totally ionized. Assuming that the time-averaged density of the fission fragments having at least one bound electron corresponds to the fission of about $N_1/2$ uranium nuclei and using Eqs. (4,5), we obtain that the ratio a of the numbers of the antiprotons, captured with ejection of the electrons by the fission fragments and uranium nuclei, is not greater than 0.17 to 0.25.

Note that the cross-section

$$\sigma^c_{at}(Z = 92, \varepsilon_{\bar{p}} \approx 5.9\,\text{MeV})$$

for capture of the antiprotons with $\varepsilon_{\bar{p}} \approx 5.9\,\text{MeV}$ by atom of metal U^{238} can be derived from the experimental data presented in Ref. [22]. About 1 % of such antiprotons was stopped in the metal U^{238} target with the mass surface density of 0.2 mg/cm^2 [22]. This corresponds to

$$\sigma^c_{at}(Z = 92, \varepsilon_{\bar{p}} \approx 5.9\,\text{MeV}) \approx 2 \times 10^{-20}\,\text{cm}^2 \quad (10)$$

The similar estimates of σ^c_{at} can also be performed using the experimental data from Ref. [25]. These estimates yield the cross-sections

$$\sigma^c_{at}(Z = 92) \approx 5.0 \times 10^{-21}\,\text{cm}^2,$$

$$\sigma^c_{at}(Z = 90) \approx 3.5 \times 10^{-21}\,\text{cm}^2,$$

$$\sigma^c_{at}(Z = 79) \approx 5.2 \times 10^{-21}\,\text{cm}^2,$$

$$\sigma^c_{at}(Z = 67) \approx 3.3 \times 10^{-21}\,\text{cm}^2$$

and the ratios

$$[\sigma^c_{at} / (\pi a_B^2 / Z^2)](Z = 92) \approx 0.48,$$

$$[\sigma^c_{at} / (\pi a_B^2 / Z^2)](Z = 90) \approx 0.33,$$

$$[\sigma^c_{at} / (\pi a_B^2 / Z^2)](Z = 79) \approx 0.37,$$

$$[\sigma^c_{at} / (\pi a_B^2 / Z^2)](Z = 67) \approx 0.17.$$

In Ref. [25] the information about the exact value(s) of $\varepsilon_{\bar{p}}$ is not presented and only the fact that the antiprotons with the initial kinetic energies of 21.23 MeV passed through three moderators, two of which had the adjustable thicknesses, is mentioned.

The probabilities of capture of antiprotons with $\varepsilon_{\bar{p}}$ of about 115 keV and greater (see below) by the uranium nuclei, fission fragments, and hydrogen isotopes with transfer of the energy to the free electrons are very low. This can be demonstrated using the model similar to that presented in Ref. [23] (Chapter VI, paragraph 17).

Let us consider collision of the antiproton with the ion with the charge eZ^*, where e is the absolute value of the electron charge. The antiproton will be captured with transfer of the energy to the free electron only if the following two conditions are satisfied.

Firstly, the parameter of the impact of the antiproton with the ion should not be greater than

$$r_0 = Z^* e^2 / \varepsilon_{\bar{p}} \quad (11)$$

This condition corresponds to the strong influence of the electric field of the ion on the antiproton trajectory. Here and below, screening of the electric field is supposed to be negligible.

Secondly, on the path of about r_0 in the vicinity of the ion the antiproton should transfer the energy of about $\varepsilon_{\bar{p}}$ to the free electron. This means that the presence of the free electron in the volume $V' \approx \pi(e^2/\varepsilon_{\bar{p}})^2 r_0$ is necessary. If $n_e V' << 1$, the probability of such a presence equals $n_e V'$.

Thus, at $n_e V' << 1$ the probability dp^c_{free} of capture of the antiproton on the path dl due to the process under consideration is given by

$$dp^c_{free} \approx n_{Z*} dl \pi r_0^2 n_e V' \approx \pi^2 n_{Z*} n_e dl e^{10} Z^{*3} / \varepsilon^5_{\bar{p}} \quad (12)$$

where n_{Z*} is the density of the ions. It is convenient to introduce the effective length $l^c_{free} \equiv dl / dp^c_{free}$ of such a capture. Eq. (12) yields

$$l^c_{free} = \frac{\varepsilon^5_{\bar{p}}}{\pi^2 n_{Z*} n_e e^{10} Z^{*3}} \quad (13)$$

Eq. (13) yields that at the negligible influence of doping on n_e

$$l^c_{free}(\rho = 200\ \mathrm{g/cm^3}, \varepsilon_{\bar{p}} \approx 115\ \mathrm{keV})[\mathrm{cm}] \approx \frac{1.43 \times 10^7}{(n_{Z*}/n_e) Z^{*3}} \quad (14)$$

(in the situation under consideration the condition $n_e V' << 1$ is satisfied for any Z^*). Substituting the parameters corresponding to the hydrogen isotopes ($n_{Z*}/n_e \approx 1$, $Z^* = 1$), uranium ($n_{Z*}/n_e \approx 10^{-3}$, $Z^* \leq 92$), fission fragments and other annihilation products into Eq. (14), we obtain the very long lengths l^c_{free}.

It is possible to show that the radiative capture of antiprotons with $\varepsilon_{\bar{p}}$ of about 115 keV and greater is also negligible.

Annihilation of antiprotons on deuterons and tritons will occur mainly in flight.

The cross-section σ_{flight} for annihilation of the antiprotons on the nucleus with the atomic mass A in flight is given by

$$\sigma_{flight}(A) \approx \sigma_H \times A^{2/3} \quad (15)$$

where

$$\sigma_H[\mathrm{mb}] = 39 + 35/p[\mathrm{GeV}/c] \quad (16)$$

is the cross-section for annihilation of the antiproton in hydrogen (or, in other words, on proton) in flight, p is the momentum of the antiproton, and c is the velocity of light [21].

Eqs. (15,16) yield

$$\sigma_{flight}(A = 2, \varepsilon_{\bar{p}} \approx 115\,\mathrm{keV}) \approx 3.9 \times 10^{-24}\ \mathrm{cm}^2 \quad (17)$$

$$\sigma_{flight}(A = 3, \varepsilon_{\bar{p}} \approx 115\,\mathrm{keV}) \approx 5.1 \times 10^{-24}\ \mathrm{cm}^2 \quad (18)$$

$$\sigma_{flight}(A = 238, \varepsilon_{\bar{p}} \approx 115\,\mathrm{keV}) \approx 9.3 \times 10^{-23}\ \mathrm{cm}^2 \quad (19)$$

Eqs. (9,19) yield that annihilation of antiprotons on the uranium nuclei in flight is negligible. It is evident that annihilation of the antiprotons on the fission fragments in flight is also negligible.

Thus, p_U is determined mainly by capture of the antiprotons by the ions of uranium and fission fragments with ejection of the electrons and annihilation in flight on the hydrogen isotopes nuclei. Assuming that $a \approx 0.25$, $\varepsilon_{\bar{p}} \approx 115\,\mathrm{KeV}$ and using Eqs. (4,8,17,18), we obtain $p_U \approx 0.6$.

Eqs. (10,13,15,16) allows us to assume that realization of $p_U \approx 1$ at $\varepsilon_{\bar{p}}$ of the order of 1 MeV is also possible. If σ^c_{at} corresponding to Eq. (10) is determined mainly by ejection of the electrons from the inner shell(s), the use of the antiprotons with $\varepsilon_{\bar{p}}$ of the order of 1 MeV will provide the relatively low cross-sections $\sigma_{flight}(A = 2,3)$ (see Eqs. (15,16)) and, probably, even the suppression of capture of antiprotons by the fission fragments. Note that the realization of the scenario with the main capture of antiprotons after their slowing down in the compressed fuel may be possible and expedient. For example, this may provide optimization of location of the hot spot (see also Ref. [10,21]). Note also that if the real cross-sections for capture of antiprotons with $\varepsilon_{\bar{p}}$ of the order of 100 keV to 1 MeV by the uranium ions in the hot spot are greater than 10^{-20} cm^2, the effective capture of the antiprotons by the uranium ions will probably occur even at $f_U < 10^{-3}$, for example, at $f_U \approx 7 \times 10^{-4}$ (here it is assumed that $\rho \approx 200$ g/cm^3; see also Eqs. (5,10)).

4. Probabilities of Fission of the Uranium Nuclei due to the Influence of Antiprotons and Other Particles and the Final Estimates of $N_{\bar{p}}$

According to Ref. [22], the probability $p^{fis}_{\bar{p}}$ of fission of the nucleus of U^{238} due to annihilation of slow antiproton is about 0.85 ± 0.15, while according to Ref. [25], $p^{fis}_{\bar{p}} \approx 0.77 \pm 0.04$. When estimating $N_{\bar{p}}$, both values of $p^{fis}_{\bar{p}}$ will be used. It seems, however, that the estimate based on the former should be considered as the main one. This corresponds to the conservative assumption about the accuracy of the available experimental data and, thereby, provides more reliable value of $N_{\bar{p}}$.

To analyze the importance of fission of the uranium nuclei due to the influence of thermonuclear neutrons and neutrons and charged pions arising due to annihilation, let us estimate the probability p_c^{fis} of such a fission of a nucleus, placed at the center of the hot spot, during heating the hot spot. Let us assume that the neutrons and pions arise in the hot spot and their scattering, expansion of the hot spot, and emission of neutrons due to fission of the uranium nuclei by the neutrons and pions are negligible. It is possible to show that according to these assumptions

$$p_c^{fis} \approx 1-\exp\{1.95\times10^4(\sigma_{n(therm)}[\mathrm{cm}^2]N_{n(therm)} + \langle\sigma_{n(an)}\rangle[\mathrm{cm}^2]N_{n(an)} + \langle\sigma_\pi\rangle[\mathrm{cm}^2]N_\pi)\} \quad (20)$$

where $\sigma_{n(therm)}$ is the cross-section for fission of the nucleus of U^{238} by thermonuclear neutrons, $N_{n(therm)}$ is the number of the thermonuclear neutrons generated in the hot spot during its heating, $\langle\sigma_{n(an)}\rangle$ and $\langle\sigma_\pi\rangle$ are the average cross-sections for fission of the nucleus of U^{238} by neutrons and charged pions, respectively, arising due to annihilation of antiprotons on nuclei of U^{238}, and $N_{n(an)}$ and N_π are the numbers of such neutrons and pions, respectively.

It is convenient to present $N_{n(therm)}$ as the product $4.25\times10^{18}\times f_b^h$, where f_b^h is the hot spot fractional burn-up corresponding to its heating. The fractional burn-up f_b corresponding to conditions (1,4) and the total time of burning the fuel seems to be about 0.38 or less (see Ref. [19]). Since $f_b^h \le f_b$ and $\sigma_{n(therm)} \approx 10^{-24}$ cm^2 (see, e.g., Ref. [26]), we obtain

$$1.95 \times 10^4 \times \sigma_{n(therm)}[\mathrm{cm}^2]N_{n(therm)} \le 3.15 \times 10^{-2} \quad (21)$$

Eqs. (4,5,20,21) show that heating the hot spot due to fission of the nuclei of U^{238} by thermonuclear neutrons can be considered as negligible. Note that if f_b^h equaled 0.38, the total kinetic energy of the thermonuclear α-particles generated in the hot spot during its heating would be about 910 kJ. Therefore, it is possible that the real contribution of the thermonuclear neutrons into p_c^{fis} is much less than 3 % (see Eqs. (2,20,21)).

Let us assume that for annihilation of the antiproton on the nucleus of U^{238} the yields of neutrons and charged pions are about 17.2 and 2.5, respectively, all of the neutrons are emitted immediately after the annihilation, and

$$\langle\sigma_{n(an)}\rangle \approx \langle\sigma_\pi\rangle \approx 2\times10^{-24}\ \mathrm{cm}^2$$

(see Refs. [3,14]). The use of these assumptions seems to result in the overestimation of p_c^{fis} (for example, the cross-sections correspond to the fission of the nucleus of Pu^{239} [3], the chosen value of the neutron yield equals its upper boundary [14]). However, even using them and assuming that all of the uranium nuclei in the hot spot undergo fission due to annihilation of the antiprotons, we obtain

$$1.95\times10^4(\langle\sigma_{n(an)}\rangle[\mathrm{cm}^2]N_{n(an)} + \langle\sigma_\pi\rangle[\mathrm{cm}^2]N_\pi) \approx 6.5\times10^{-3}$$

This and Eqs. (4,5,20) show that fission of the uranium nuclei by the annihilation products is negligible. Note that Eq. (20) does not take into account fission of the nucleus of U^{238} by the products of annihilation of antiprotons on deuterons, tritons, and fission fragments. It is easy to show that this assumption is valid.

It is evident that $N_{\bar{p}} = N_1/(p_U p_{\bar{p}}^{fis})$. Assuming that $p_U \approx 0.6$ to 1 and using the aforementioned value of N_1 and $p_{\bar{p}}^{fis}$ from Ref. [22], we obtain

$$N_{\bar{p}} \approx (1.3 \text{ to } 4.4)\times10^{15} \quad (22)$$

while $p_{\bar{p}}^{fis}$ from Ref. [25] corresponds to

$$N_{\bar{p}} \approx (1.6 \text{ to } 4.2)\times10^{15} \quad (23)$$

It is interesting that Eqs. (22,23) yield the values of $N_{\bar{p}}$, the lower boundaries of which are rather close to the value $N_{\bar{p}} \approx 6.2\times10^{14}$ presented in Ref. [10]. Some of the assumptions used in Ref. [10] are the following. It was assumed that $f_U = 0.01$, $\rho = 300$ g/cm^2 (the relative contribution of hydrogen isotopes into ρ was about 50 %), and $p_{\bar{p}}^{fis} \approx 0.8$. It was assumed that the energy transferred to the fuel in the hot spot due to annihilation of antiproton on the uranium nucleus was about 700 MeV. The ratio of the effective cross-sections determining the probabilities of annihilation of antiprotons on the nuclei of uranium and hydrogen isotopes was assumed to be about 6.8 (this value equals the squared ratio of the uranium outer electron radius to a_B). Thus, the models presented in this paper and Ref. [10] are very different (see also Introduction), and the existence of some similarity of the results should be considered as accidental.

5. Possible Scenario of Delivery of Antiprotons to the Hot Spot

In many scenarios of acceleration of the space ships the yield of the microexplosion or the group of microexplosions, ignited simultaneously or almost simultaneously, can be rather high, while the target can or even must contain the significant amount of the auxiliary material(s) [3,6,7,10,27-29]. This may provide the possibility to focus the antiprotons or antihydrogen molecular or cluster ions on the hot spot using the thin foil or/and wire electrodes creating the magnetic fields. If necessary, the electrodes will contact the target. The main electric pulses will pass through the electrodes or/and through the plasma arising from them due to the influence of the "prepulses" (for the sake of brevity, in this paper the term "electrodes" is being used to describe all the parts conducting the electric current and/or transforming into the plasma clouds conducting the electric current). The similar electrodes may also be used in other scenarios of ignition of thermonuclear microexplosions and initiation of fission and fission – fusion microexplosions with the use of antimatter, for example, to focus the antiparticles on the converter(s) of the indirect drive or indirect compression, fast ignition target (see also Refs. [3-10]).

The use of the proposed thin electrodes is an analog of the use of the thin foils to transmit the electric pulses to the Z-pinch driven targets as proposed in Ref. [30].

Recycling of the material(s) of the electrodes in the space propulsion system and the effective use of this material as an additional propellant seem to be impossible. Therefore, operation of the focusing system under consideration will be effective only if its mass is much less than the total mass of the target. It seems that this condition will be satisfied mainly in the situations when the mass of the propellant is sufficiently high. Note that the microexplosion ignited with the use of the antimatter can be used to ignite one or several microexplosions without the use of the antimatter or with the use of a relatively small amount of the antimatter (see also Refs. [6,27-29]). The mass of the propellant heated by the group of microexplosions can be rather high. Also the high yield of the group of microexplosions and even of the only microexplosion is a factor providing the possibility to focus the antiparticles using the high-energy electric pulse(s).

The possibility of the strong focusing of the antiparticles may provide the possibility to decrease both E_{ign} and $N_{\bar{p}}$ by means of an increase in ρ (see also Ref. [12]). However, the real dependence $N_{\bar{p}}(\rho)$ will be known only when the dependence of the optimum value of f_U on ρ is found.

Note that placement of antihydrogen ice, or antiprotons, or antiproton – positron plasma inside the noncompessed target (see Refs. [2,8-10]) seems to be impossible or at least very dangerous because of the possibility of development of the chain reaction of annihilation (see also Refs. [24,31] and a bibliography therein).

6. Conclusion

Eq. (22) yields a rather wide range of $N_{\bar{p}}$: the ratio of its upper and lower boundaries exceeds 3. This ratio can be presented as a product of the factors of about 1.4, 1.4, and 1.7, that equal the ratios of the upper and lower boundaries of E_{fr}, $p_{\bar{p}}^{fis}$, and p_U, respectively. The ratio of the upper and lower boundaries of $p_{\bar{p}}^{fis}$ may be about 1.1 [25]. However, even in such a case the indeterminacies of the experimental results and the theoretical estimate bring the comparable contributions into the indeterminacy of $N_{\bar{p}}$ and the ratio of the upper and lower boundaries of $N_{\bar{p}}$ is rather large, namely, about 2.6 (see Eq. (23)).

Heating the hot spot due to the transfer of the kinetic energies of the antiprotons and other effects that are not taken into account in the requirement on N_1 may provide some decrease in $N_{\bar{p}}$. The maximum relative value of this decrease seems to be about 10 to 20 %.

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