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Research Article

Analysis of the p-^{11}B Fusion Scenario with Compensation of the Transfer of Kinetic Energy of Protons and Alpha Particles to the Gas Medium by the Electric Field

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The energy balance of the p-^{11}B fusion scenario with compensation of the transfer of kinetic energy of protons and alpha particles to the gas medium by the electric field is considered. It is shown that such scenario cannot provide the use of p-^{11}B fusion reaction for power production due to the very low ratio of the energy release of the fusion reaction to the energy necessary for compensation. The upper boundary of this ratio is about 2×10^{-3}.

1. Introduction

The influence of chain reactions on the rate R_1 of p-^{11}B fusion reaction

$$\mathrm{p} + {}^{11}\mathrm{B} \longrightarrow 3\alpha + 8.7\,\mathrm{MeV}, \tag{1}$$

is discussed since 1973 [1–12]. One of the chain reactions consists of the scattering of at least one of the three alpha particles, generated by reaction (1), on proton(s) with acceleration of the proton(s) to kinetic energies, corresponding to a relatively high cross-section σ_1 for reaction (1) and the subsequent participation of the accelerated proton(s) in this reaction [1, 4, 6–12]. According to [1], at the temperature of 150–350 keV and the density of 10^{16}–$10^{26}\,\mathrm{cm}^{-3}$, this chain reaction and other "nonthermal" effects result in an increase in R_1 on 5–15%. The type of particles with such densities was not mentioned [1], but this detail is not essential because in plasma under consideration, the densities of all particles are comparable [8]. According to [2–4, 7, 9, 10, 12], at least if special measures are taken, the increase in R_1 due to the chain reactions can be so high that it will provide the possibility of the use of reaction (1) for power production. The negative results of analysis of such assumptions from [2–4] are presented in [5, 6, 8, 11].

In 2020, Eliezer and Martinez-Val [9] and Eliezer et al. [10] proposed p-^{11}B fusion scenarios with the influence of electric and magnetic fields on protons and alpha particles in the gas medium. The main idea of the proposal is that during some time periods, time-dependent electric field should compensate approximately for the transfer of kinetic energy ε_p of a proton with $\varepsilon_p \approx \varepsilon_p^*$, where ε_p^* is ε_p corresponding to the largest value of σ_1 for the collision of proton with the nucleus of ^{11}B in the rest, to the medium and for transfer of the kinetic energy of the alpha particle to the medium [9, 10]. This compensation should increase the probability of participation of the protons in reaction (1) and that of "useful" acceleration of protons due to the scattering of alpha particles on them. The magnetic field should provide the realization of these scenarios in reactors with acceptable sizes [9, 10]. Below, it is shown that in the scenario proposed in [10], the ratio g of energy release of reaction (1) to the average value $\langle W_s \rangle$ of the energy spent for the initiation of one reaction (1) will be unacceptably low for power production.

2. The Upper Boundary of g

Eliezer et al. [10] analyzed the situations when reaction (1) occurs in gaseous $H_3{}^{11}B$ or other hydride of ^{11}B with a density of $10^{19}\,\mathrm{cm}^{-3}$ or of the order of $10^{19}\,\mathrm{cm}^{-3}$ and temperature of about 1 eV or few eV. Ionization of this gas is supposed negligible [10]. Since a free molecule of H_3B does not exist and at the temperature above 700°C all hydrides of boron dissociate into boron and hydrogen [13], we will estimate the lowest boundary W_s^l of $\langle W_s \rangle$ in gas medium consisting of atoms of ^{11}B with the density

$$n_{11B} \approx 2.5 \times 10^{18}\,\mathrm{cm}^{-3}, \tag{2}$$

and molecules of H_2 with the density

$$n_{H2} \approx 3.75 \times 10^{18}\mathrm{cm}^{-3}. \tag{3}$$

At the conditions described in [10], the medium containing atoms of boron and molecules of hydrogen will also contain atoms of hydrogen and ions, but this is not essential for the analysis of the acceptability of attainable values of g for power production. The ratio n_{11B}/n_{H2} corresponds to the ratio of the numbers of nuclei of ^{11}B and protons in the nonexisting free molecule of $H_3{}^{11}B$ discussed in [10]. The choice of n_{11B} corresponds to an example presented on page 5 of Reference [10] and is mainly important for an estimate of the typical proton path $l_{typ} = 1/(\sigma_1 n_{11B})$, corresponding to one reaction (1). The estimate of W_s^l presented below yields that this parameter is independent of n_{11B}.

In the situation under consideration, the change $d\varepsilon_p$ of ε_p on proton path dx is given approximately by

$$d\varepsilon_p \approx \left[eE - k_{H2}^p(\varepsilon_p)n_{H2} - k_B^p(\varepsilon_p)n_{11B}\right]dx, \tag{4}$$

where e is the proton charge, E is the strength of the electric field, and k_{H2}^p and k_B^p are the parameters describing the transfer of ε_p to molecules of hydrogen and atoms of boron, respectively. The parameter k_{H2}^p was calculated as

$$k_{H2}^p = 2\,A_H\,m_u\,S_{H2}^p, \tag{5}$$

where A_H is the atomic mass of hydrogen, m_u is the atomic mass unit, and S_{H2}^p is the stopping power of molecular hydrogen for proton. The parameter k_B^p was calculated as

$$k_B^p \approx \frac{m_u}{2}\left(A_{Be}\,S_{Be}^p + A_C\,S_{Cam}^p\right), \tag{6}$$

where A_{Be} is the atomic mass of beryllium, S_{Be}^p is its stopping power for proton, A_C is the atomic mass of carbon, and S_{Cam}^p is the stopping power of amorphous carbon with the density of 2 g/cm^3 for proton. The values of S_{H2}^p, S_{Be}^p, and S_{Cam}^p from [14] were used.

The parameter k_B^p was approximated by (6) due to the absence of data on the stopping power of boron for proton in [14]. This equation corresponds to the assumption that the product P of the stopping power of the medium, consisting of atoms or molecules of one chemical element with atomic number Z, on the atomic mass of this element depends on Z approximately linearly and, therefore,

$$P(Z) \approx [P(Z - \Delta Z) + P(Z + \Delta Z)]/2, \tag{7}$$

where ΔZ is a small natural number, for example, unity or two. In order to demonstrate that at least in some situations, the accuracy of (7) is rather high, let us compare $P(Z = 6,\ \varepsilon_p = 600\,\mathrm{keV}) \approx 3797\,\mathrm{MeV\,cm^2\ g^{-1}}$ and $P(Z = 6,\ \varepsilon_p = 700\,\mathrm{keV}) \approx 3440\ \mathrm{MeV\,cm^2\,g^{-1}}$, calculated using S_{Cam}^p from [14], with the same parameters, calculated using (7) and $\Delta Z = 2$. Substituting S_{Be}^p and the stopping power of molecular oxygen for proton from [14] into (7), we obtain $P(Z = 6,\ \varepsilon_p = 600\,\mathrm{keV}) \approx 3773\,\mathrm{MeV\,cm^2\ g^{-1}}$ and $P(Z = 6,\ \varepsilon_p = 700\,\mathrm{keV}) \approx 3424\,\mathrm{MeV\,cm^2\,g^{-1}}$. Thus, in these cases, the relative accuracy of (7) is better than 1%. This allows us to assume that at $600\,\mathrm{keV} \le \varepsilon_p \le 700\,\mathrm{keV}$ (see below), the relative accuracy of (6) is of the order of 1% or even better.

According to [15], $\varepsilon_p^* \approx 646.2\,\mathrm{keV}$ and

$$\sigma_1\left(\varepsilon_p = \varepsilon_p^*\right) \approx 1.196\,\mathrm{b}. \tag{8}$$

Let us denote the value of E corresponding to the condition $d\varepsilon_p/dx = 0$, i.e., to the almost exact compensation of the transfer of kinetic energy of protons to the gas medium by the electric field, as E_0. This value depends on ε_p ((4)). Equations (2)–(6) and (8)) yield that at $\varepsilon_p = \varepsilon_p^*$, $l_{typ} \approx 3.34 \times 10^5$ cm, $E_0 \approx 24.9$ kV/cm, $e\,E_0\,l_{typ} \approx [k_{H2}^p(n_{H2}/n_{11B}) + k_B^p]/\sigma_1 \approx 8.32$ GeV, and $(8.7\,\mathrm{MeV})/(eE_0\,l_{typ}) \approx 1.046 \times 10^{-3}$.

At $\varepsilon_p \approx \varepsilon_p^*$, k_{H2}^p and k_B^p decrease with increasing ε_p ((5) and (6) and [10, 14]). This results, in particular, in the impossibility to provide a stable motion of proton with such kinetic energy at constant E [10]. The highest value of $1/(eE_0\,l_{typ})$ corresponds to $\varepsilon_p \approx 657.6$ keV, $E_0 \approx 24.6$ kV/cm, $l_{typ} \approx 3.36 \times 10^5$ cm, $eE_0 l_{typ} \approx 8.27$ GeV, and $(8.7\,\mathrm{MeV})/(eE_0\,l_{typ}) \approx 1.052 \times 10^{-3}$. These values of $eE_0 l_{typ}$ and $(8.7\,\mathrm{MeV})/(eE_0\,l_{typ})$ can serve as W_s^l and the upper boundary of g, respectively. It should be emphasized that the real value of $\langle W_s \rangle$ can be much greater than $eE_0 l_{typ}$ due to acceleration of secondary charged particles, i.e., molecular ions of hydrogen, protons, ions of ^{11}B, and electrons created by the fast protons considered above and alpha particles, etc. [16–18]. At sufficiently high temperature, the acceleration of electrons and ions arising due to thermal ionization can also be important. The problem of the possibility of electric breakdown in the gas medium under consideration can probably be solved only experimentally. The presented estimate of W_s^l corresponds to the assumption that the magnetic field prevents the acceleration of electrons and relatively slow molecular ions of hydrogen, protons, and ions of ^{11}B by the electric field. However, the accuracy of this estimate is sufficient for the reliable qualitative conclusion about the unacceptability of the scenario proposed in [10] for power production: in any case, $\langle W_s \rangle$ will include $eE_0 l_{typ}$ and, therefore, g will be too low. The reason is that the efficiency of the use of any fusion reaction for power production will be determined, in particular, by the cost of electricity [19, 20]. According to [20], for the inertial fusion energy power plant with conversion of fusion energy into thermal energy and subsequent conversion of 30–35% of the latter into electricity, the cost of electricity will be acceptable

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when the product of the target gain on the driver efficiency η_d exceeds ten. The target gain is the ratio of fusion energy release of one microexplosion to the energy delivered to the target for ignition of the microexplosion [20]. This parameter should exceed ten even if η_d is close to unity and is an analog of the parameter g. Thus, g of the order of 10^{-3} and less is not sufficient for power production involving conversion of fusion energy into thermal energy. Note that Weaver et al. [1] discussed briefly the potential feasibility of power production in the regime of subignition operation corresponding to $g < 1$. In any case, g of the order of 10^{-3} and less seems to be too low even for this regime.

Note also that in the scenario proposed in [10], the acceleration of alpha particles, if it is not suppressed by the magnetic field, will not provide the effective acceleration of protons and, therefore, will serve mainly as a process increasing $\langle W_s \rangle$. This can be shown using equations, similar to (4)–(6), and the data from [10, 11, 14, 21] for the analysis of the motion of alpha particles and the transfer of their kinetic energy to protons. The compensation of deceleration of protons in the gas medium consisting mainly of atoms of ^{11}B will also not provide sufficiently high values of g: at $n_{H2} = 0$, the highest value of $1/(eE_0 l_{typ})$ corresponds to $\varepsilon_p \approx 656.6\,\text{keV}$, $eE_0 l_{typ} \approx 4.30\,\text{GeV}$, and $(8.7\,\text{MeV})/(eE_0 l_{typ}) \approx 2.024 \times 10^{-3}$.

3. Conclusion

The scenario proposed in [10] cannot be used for effective power production due to the very low attainable g, the upper boundary of which is about 10^{-3}. A decrease in n_{H2}/n_{11B2} down to zero can result only in an approximately two-fold increase in the upper boundary of g. The real value of g can be much less than its upper boundary.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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