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Research Article

Mechanism and Dynamics of Quasi-Stationary Self-Supporting LENR in Low-Temperature Magnetized Plasma

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Abstract

The physical foundations for the production of effective self-controlled low energy nuclear fusion in a magnetized deuterium or hydrogen cold plasma are considered. The LENR mechanism is associated with the features of the charge state of individual particles of cold plasma, which corresponds to the fluctuation alternation of ionization and recombination processes of each atom in such plasma with thermal energy $kT \approx 10 - 20eV$. Each act of ionization of any hydrogen atom in the presence of a constant magnetic field corresponds to the creation of a harmonic oscillator, which continues to exist until the moment of recombination of this atom. The impulsive process of creating of such an oscillator based on a proton or deuteron is accompanied by the formation of quantum coherent correlated states of these particles in created harmonic oscillator, which are characterized by giant fluctuations of kinetic energy. The magnitude of these fluctuations reaches 30 – 100 keV and exceeds the temperature of low-temperature plasma by 10^3 – 10^4 and more times. For particles with such energy, the probability of nuclear fusion during interaction with nearest atoms or ions is very high.

Keywords: Nuclear fusion, low-temperature plasma fusion, atoms ionization and recombination, coherent correlated states, energy fluctuations

1. Introduction

Traditional methods and mechanisms of producing nuclear reactions at low energy (LENR) are based on several basic concepts:

- controlled very essential change in the critical characteristics (heating or acceleration) of the interacting particles;
- purposeful change in the characteristics of the nearest environment of the material media in which the interacting particles are located (intense compression, change in the density of the electron or muon environment, change in the phase or physical volume etc.);
- hypothetical short-term change in the charge state of the individual protons due to its transformation into a neutron by weak interaction with accelerated electrons, which solves the problem of the Coulomb barrier.

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To implement these mechanisms, special methods are required. Each of them is a one-time phenomenon. To repeat them, it is necessary to repeat the entire cycle of external influences. Such a one-time nature of the manifestation of these methods and the associated lack of multiple regular repetitions of nuclear processes are among the fundamental reasons for the unreliability and non-optimality of the existing methods for producing LENR.

In this paper an effective mechanism of self-regulating stimulation of quasi-stationary LENR is described. This mechanism is connected with fundamental phenomena of thermal equilibrium in multiparticle systems and is produced in the cyclical natural alternation of the processes of ionization of atoms and recombination of ions occurs, lasting indefinitely.

2. Peculiarities of LENR Produced by an Impulsive Change in the Charge State of an Interacting Particle

It is obvious that the starting prerequisite for the implementation of any nuclear reaction involving charged particles is to ensure a high probability that these particles will pass through the Coulomb potential barrier. One of the most effective methods for overcoming the Coulomb barrier in the implementation of nuclear fusion at low energy is the use of coherent correlated states (CCS) of a particle.

Such states are characterized by both very large (giant) and very long (compared to uncorrelated states) fluctuations of energy and momentum of this particle. These states correspond to the modified Schrödinger-Robertson uncertainty relations [1]–[4]

$$\delta p\delta q \geq \frac{\hbar}{2\sqrt{1-r^2}} \equiv \hbar_{eff}/2, \hbar_{eff} = \hbar/\sqrt{1-r^2} \equiv G\hbar, r = \frac{<qp>+<pq>}{2\sqrt{<p^2><q^2>}};$$
$$\delta E\delta t \geq \frac{\hbar}{2\sqrt{1-r^2}} \equiv \hbar_{eff}/2, \quad \hbar_{eff} = \hbar/\sqrt{1-r^2} \equiv G\hbar, r = \frac{<Et>+<tE>}{2\sqrt{<E^2><t^2>}}, \tag{1}$$

which are the universal generalization of Heisenberg uncertainty relations at $r \neq 0$.

In these relations parameter r is the correlation coefficient the value of which corresponds to the interval $-1 \leq r \leq 1$. This coefficient characterizes the degree of mutual connection of corresponding dynamic variables p, r and E, t. An alternative characteristic of such states is the correlation efficiency coefficient $G = 1/\sqrt{1-r^2}$.

The simplest and most efficient method for creating of such states can be implemented in a non-stationary harmonic oscillator. It was shown in the works [5]–[14] that fast modulation of the parameters of such an oscillator leads to the formation of a CCS and to the generation of very large fluctuations of the momentum δp and energy δE of the particle. The same effect corresponds to the motion of a particle in a spatially inhomogeneous system of potential wells (in particular, in a channel between atomic planes in crystals [15]–[19]).

The physical basis for such processes is the in-phase mutual interference of different eigenfunctions of the same particle in this system.

From formula (1) a simple estimate for the lower limit (minimum value) of fluctuations of the kinetic energy follows:

$$\delta E^{(\min)} = (\delta p)^2/2M = G^2\hbar^2/8M(\delta q)^2, \tag{2}$$

where M is a particle mass and δq is the spatial interval, where the particle is localized.

It is important to note that this lower limit corresponds to the case when the particle in the parabolic potential corresponding to the harmonic oscillator in the ground state, the lowest state with $E(0) = \hbar\omega/2$ before the deformation of the potential well started. In a more realistic case, when the initial state of the particle corresponds to the excited state of the oscillator with the energy $E(n) = \hbar\omega(n + 1/2)$ the corresponding expression for the minimal energy of fluctuation has the following form:

$$\delta E^{(\min)} = G^2 E(n). \tag{3}$$

This case also corresponds to the thermal energy of the medium with $E(n) = kT$ where such an oscillator is located and leads to the following formula for effective thermal fluctuation:

$$\delta T = G^2 T(n). \tag{4}$$

An analysis [5]–[17] of the dynamics of the CCS formation process in such non-stationary systems shows that the realistic value of the coefficient G for such a change in the frequency of the effective oscillator can reach very large values $G \geq 10^2 - 10^3$ and depends on the parameters of the nonstationary oscillator.

In the works [3]–[5] it was shown that the correlation coefficient r

$$r = \mathrm{Re}\left\{\varepsilon^* \frac{d\varepsilon}{dt}\right\} \Big/ \left|\varepsilon^* \frac{d\varepsilon}{dt}\right| \tag{5}$$

can be calculated based on the solution of the equation of a classical oscillator with a variable frequency

$$\frac{d^2\varepsilon}{dt^2} + \omega^2(t)\varepsilon = 0 \tag{6}$$

under the initial conditions

$$\varepsilon(0) = 1, \left.\frac{d\varepsilon}{dt}\right|_0 = i \tag{7}$$

In these equations $\omega(t) = 1 + f(t)$ is the dimensionless nonstationary frequency, which is normalized to the initial frequency of the oscillator $\omega_0 = \omega(0); t$ is the dimensionless (normalized to ω_0^{-1}) time; $\varepsilon(t)$ is the dimensionless (normalized to $q_0 = \sqrt{\hbar/M\omega_0}$) complex coordinate of the particle.

Let us consider the dynamics of the formation of a coherent correlated state in a pulsed (close to stepwise) mode of increasing the oscillator frequency

$$\omega(t) = \omega_0 \left\{1 + (g-1)\left[1 - e^{-t/\tau}\right]\right\} = \omega_0 \left\{1 + (g-1)\left[1 - \exp\left(-\frac{\omega_0 t}{\omega_0 \tau}\right)\right]\right\} \tag{8}$$

from the initial value ω_0 to the final value $\omega(t \to \infty) = \omega_0 g \equiv \omega_{\max}$ with a characteristic turn-on time τ for different values of the final change in the frequency of the oscillator $g = \omega_{\max}/\omega_0$.

One of the most realistic models of such an oscillator is associated with the motion of a particle with a charge Q and with a mass M in a magnetic field H [8], [9]. In such a system, all parameters of particle motion, including eigenfunctions $\varphi_n(q)$, frequency $\omega_H = QH/Mc$ and the spectrum of energy levels $E_n = \hbar\omega(n + 1/2)$, fully correspond to the mathematical model of a harmonic oscillator. With each act of a very sharp switching on of the magnetic field, a coherent correlated state of ions located in the region of action of this field forms. This problem has been considered in detail in [20].

The subsequent analysis shows that for the problem of the motion of an ion in the volume of a low-temperature plasma in a realistic (moderate in amplitude) constant magnetic field, we have the following inequality $\omega_H \tau << 1$. For the problem considered in this work, this parameter is equal to the value $\omega_H \tau \approx 10^{-8}$.

If we take into account that the time of existence of the CCS is much greater than the period of the main frequency $\omega_{\max} = \omega_H$, then the last condition actually corresponds to a purely stepwise mode of switching the oscillator frequency.

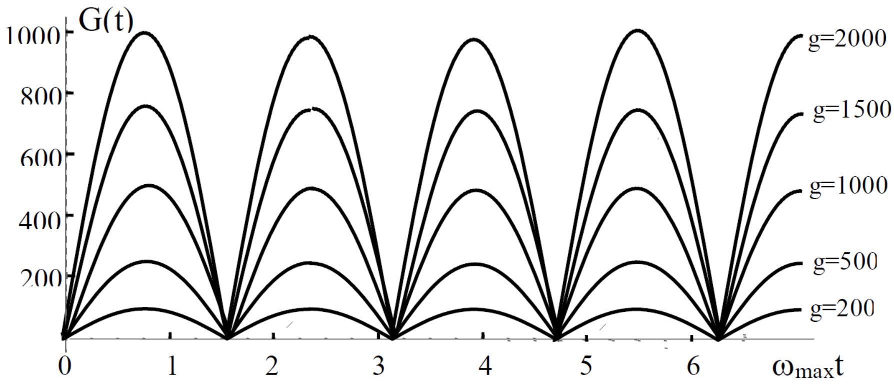

Figure 1. Non-stationary dynamics of the correlation efficiency coefficient G after increasing of the base oscillating frequency $\omega(t)$ in g times related to initial value ω_0.

The results of calculation of the correlation efficiency coefficient $G = 1/\sqrt{1-r^2}$ for different g at condition $\omega_H\tau << 1$ are presented in Fig. 1.

It can be seen that in this mode of the oscillator frequency change, a very large value of the coefficient is produced. Direct analysis shows that all these dependencies $G(t)$ are very well approximated by a simple formula $G(t) = G_{\max}(g)\,|\sin(2\omega_H t)|$.

This approximation corresponds to the relation

$$\left\langle G^2 \right\rangle = G^2_{\max}(g)/2. \tag{9}$$

At first glance, it seems that for the production and practical use of such an effect, we need a system that generates very fast and frequent changes in the magnetic field strength. The difficulties of creating such a system are obvious.

A detailed analysis shows that there is a realistic mechanism that allows this process to be generated in a completely stationary plasma! For this, it is necessary to take into account the features of the real microdynamics of multiple repeated mutual transformations of atoms and ions that occur in a stationary low-temperature hydrogen plasma. Such features of plasma microdynamics are associated with the continuous alternation of the processes of ionization and recombination of atoms and ions at a plasma temperature close to the ionization potential of its atoms and exceeding the characteristic potential of dissociation of hydrogen molecules into atoms. In such a plasma, each act of ionization corresponds to a pulsed switching on of the interaction of the formed ion with a magnetic field and the formation of a short-term CCS, and each recombination event corresponds to a pulsed switching off of the interaction and also the formation of a short-term CCS due to the interference of those spatially distributed wave functions that, before the recombination act, formed a coherent correlated superposition.

Such a fundamentally new mechanism for changing the frequency $\omega(t) = Q(t)H/Mc$ of an effective harmonic oscillator, corresponding to the process of interaction of ions with a magnetic field, is based not on the traditional change in the parameters of the magnetic field with a constant charge of the ion, but on the action of a constant magnetic field and a self-controlled change in the effective charge of the ion, when it is turned on and off in turn in the processes of ionization and recombination.

Obviously, such a process can be the most efficient in a plasma containing atoms with one electron (hydrogen or deuterium). For heavier atoms, the efficiency of this process has to be significantly lower due to two main reasons:

- the process of single ionization or recombination does not allow the interaction of a particle with a magnetic field to turn off completely, which leads to a small value of the parameter $g = \omega_{\max}/\omega_0$ and, accordingly, to a small value of the correlation efficiency coefficient,
- the presence of electrons in the ion shell after partial ionization greatly increases the probability and cross-section of scattering of these ions in the plasma volume, which leads to a rapid dephasing of coherent states and a very short lifetime of the CCS.

Of course, heavier atoms can also be present in such plasma, but they will be a "passive target" for hydrogen or deuterium atoms, which, with such a switch, will receive a very large fluctuation of kinetic energy.

In such a system the value $\tau = \tau_{ion}$ characterizes the process of switching on the ion charge, which corresponds to the duration of the process of changing the frequency of the equivalent non-stationary harmonic oscillator. The value

$$\tau_{ion} \approx R_D/v_e = \sqrt{m_e/4\pi n_e e^2} \tag{10}$$

is determined by the speed v_e of plasma electrons incident on the atom, whose energy exceeds the ionization potential, and by their distance from the atom (it can be estimated through the Debye screening radius $R_D = \sqrt{kT_e/4\pi n_e e^2}$), at which the moving electron can affect the state of the atom; and is equal to $\tau_{ion} \approx 2 \times \left(10^{-13} - 10^{-14}\right)$ sec in plasma with parameters $T_e = 10 - 20\text{eV}$, $n_e = 10^{16} - 10^{18}\ \text{cm}^{-3}$.

The initial time of "turning on the charge" $Q(t)$ of an ion during neutral atom ionization can be determined by Heisenberg uncertainty relation, according to which any atom can be in an ionized state for a time $\delta t \geq \hbar/2\delta E = \hbar/2E_{ion} = 1/2\omega_{ion}$ due to the quantum mechanical fluctuation $\delta E \geq E_{ion}$ of the electron energy. Such a fluctuating initial ionization of an atom does not lead to the excitation of a real vibrational state of the nucleus in an external magnetic field, but does allow it to establish the initial frequency ω_0 of such vibrations after the beginning of real ionization. According to such an analysis, a dynamically reliable (non-virtual) process of "switching on" the mechanism of hydrogen atom ionization actually begins after a very short time $\delta t \approx 1/2\omega_{ion} \approx 2 \times 10^{-16}$ sec.

Taking into account this circumstance and condition $\tau_{ion} \gg \delta t$, the base equation (8), which characterizes the one cycle of "turning on" the charge, can be represented in its original form

$$\omega(t) = \omega_H \left\{1 - \exp\left(-\frac{\delta t + t}{\tau_{ion}}\right)\right\}. \tag{11}$$

It is possible to prove that (11) can be reduced to (8) by the following mathematical transformation:

$$\omega(t) \approx \omega_H \left\{1 - \left(1 - \frac{\delta t}{\tau_{ion}}\right)\exp\left(-\frac{t}{\tau_{ion}}\right)\right\} = \omega_0 \left\{1 + (g-1)\left(1 - \exp\left(-\frac{t}{\tau_{ion}}\right)\right)\right\}. \tag{12}$$

Here

$$g = \tau_{ion}/\delta t \approx \omega_i \sqrt{m_e/\pi n_e e^2}, \omega_0 \equiv \omega(0) = \omega_H/g. \tag{13}$$

It can be seen from these estimates that in the case of a typical magnetic field of $H \approx 1000 - 3000 Oe$ in a plasma with a density $n_e = 10^{16} - 10^{18}\ \text{cm}^{-3}$, the frequency increase parameter g of the equivalent oscillator is equal to value $g \approx 100 - 1000$, which agrees with the data presented in Fig. 1.

The duration of the existence of such a correlated state with the accompanying giant fluctuations in the kinetic energy of charged particles can be estimated as the time from the moment of creation of such a CCS to the first collision of this particle with surrounding atoms and ions

$$\Delta t_{ion}^{(corr)} \approx < l > /v_i \approx \sqrt{(kT_i)^3 M_i}/4\pi n_i e^4 \Lambda. \tag{14}$$

Here $v_i \approx \sqrt{kT_i/M_i}$ is the isothermal velocity of a heavy ion (proton) in a given medium, $< l > \approx (kT)^2/4\pi n_e e^4 \Lambda$ - free path length, $\Lambda \approx 5...10$ - Coulomb logarithm.

During such a collision, there is a partial violation of the optimal phase relationships between different eigenfunctions of a particle in a strictly phased superposition state of a harmonic oscillator, which, of course, immediately sharply reduces the correlation coefficient.

If we take into account that in the coherent correlated state the effective energy of the particle increases by a factor of G^2, then to estimate $\Delta t_{ion}^{(corr)}$ from formula (14) the replacement

$$T_i \to < G^2 >_t T_i \tag{15}$$

should be made, which leads to a very significant increase of the lifetime $\Delta t^* \sim \left\{ \left\langle G^2 \right\rangle_t \right\}^{3/2}$ of the CCS. In particular, for $kT_i = 10\text{eV}$ and $n_i = 10^{16} - 10^{18}\ \text{cm}^{-3}$, the time $\Delta t_{ion}^{(corr)}$ increases from $\Delta t_{ion} \approx 10^{-9} - 10^{-11}\,\text{sec}$ for the uncorrelated state to $\Delta t_{ion}^{(corr)} \approx 10^{-3} - 10^{-2}\,\text{sec}$ for the values of $< G > \approx 200 - 800$. This time is $10^4 - 10^5$ times longer than the oscillation period ω_H of the harmonic oscillator, which corresponds to the frequency of the proton in a magnetic field H with a strength of 1000–3000 Oe.

It should be noted that the total disintegration of the CCS takes place only after several successive collisions, which increases the time $\Delta t_{ion}^{(corr)}$ by several times and contributes to a more efficient use of the CCS.

3. Dynamics of CCS Formation and LENR Generation Under Natural Alternation of Ionization and Recombination Processes in Low-Temperature Magnetized Plasma

The process considered above, of CCS formation during the ionization of atoms in plasma, is part of one stage of the cyclic process. This process consists in the repeated alternation of the ionization and recombination of atoms in a low-temperature plasma.

Each stage of this cyclic process consists of several substages:

a) The initial part of every stage starts with the time interval (average duration $\langle t_{atom} >$) of the existence of an atom before the beginning of the ionization process

$$< t_{atom} >= 1/ < \sigma_{ion}\left(v_e\right) v_e > n_e = \left\{ C_H n_e \left(kT_e\right)^{3/2} \sqrt{\frac{8}{\pi m_e}} \left(\frac{V_i}{kT_e} + 2 \right) \exp\left(-\frac{V_i}{kT_e} \right) \right\}^{-1}. \tag{16}$$

Here V_i is the ionization potential of an atom; $C_H \approx 6 \cdot 10^{-18}\ \text{cm}^2/\text{eV}$ is a parameter depending on the structure of the cross section $\sigma_{ion}(v)$ of the hydrogen ionization process [21].

Using this result, it is possible to determine the typical average duration of atomic state of the particle

$$< t_{atom} > \approx \left(10^8 - 10^9\right)/n_e \approx 10^{-7} - 10^{-10}\text{sec}, \tag{17}$$

corresponding to the plasma temperature $kT_e = 10 - 20\text{eV}$ and electron (ion) concentration $n_i = 10^{16} - 10^{18}\ \text{cm}^{-3}$.

b) The substage of a neutral atom ends with the process of direct ionization. Its characteristic duration corresponds to the value τ_{ion} (10) and is equal to the short duration $\tau_{ion} \approx 2 \times \left(10^{-13} - 10^{-14}\right)$ sec in the same plasma.

c) The next parameter determines the characteristic (average) time

$$< t_{ion} >= n_e n_i / n_a n_e^2 < \sigma_{ion}(v) v_e >= K < t_{atom} >, K = n_i/n_a = n_i/\left(n_{a0} - n_i\right) \tag{18}$$

of existence of the ionized state of a hydrogen isotopes until the moment of recombination and transformation into an atom [22]–[25]. This time differs by a large factor (Saha formula)

$$K \approx 4 \frac{\left(m_e kT_e/2\right)^{3/2}}{\hbar^3 n_{a0}} \exp\left(-V_i/kT_e\right) >> 1 \tag{19}$$

from the similar average lifetime $< t_{atom} >$ of the same particle in the form of an atom.

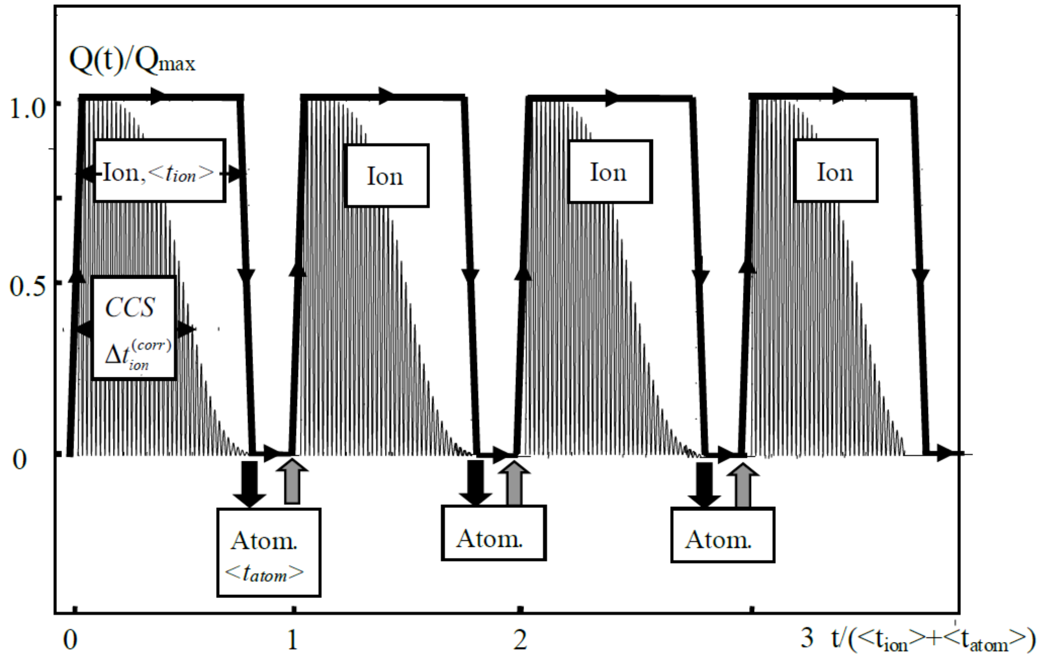

Figure 2. The sequence of existence of coherent correlated states and the dynamics of turning on and off the hydrogen effective charge Q(t).

Result (19) with $K >> 1$ is valid in the considered temperature range $kT_e \approx 10 - 20$eV under the obvious condition that the total concentration of particles in a plasma $n_{a0} << 10^{24}$ cm^3, i.e. much less than in a solid. From the condition $K >> 1$, it can be seen that the average time $< t_{ion} >$ of existence of hydrogen and its isotopes in the form of a free nucleus and a free electron in such a plasma is much longer than the similar time of existence of these particles in the form of atomic hydrogen, i.e. the time $< t_{atom} >$ required for the subsequent rapid ionization of atoms in the same plasma.

d) The final part of the direct recombination process is close in order of magnitude to the analogous duration τ_{ion} of the direct ionization process, and its duration is much shorter than $\langle t_{ion} \rangle$.

The given parameters may differ by several times when additional factors such as multistage ionization or ionization from a pre-excited state of the atom are taken into account. These corrections do not change the general trend: the duration of existence of the self-stimulated coherent correlated state of the hydrogen ion in a magnetized low-temperature plasma is the major part of the duration of each stage of ionization-recombination cycle.

Estimations show that in a partially ionized magnetized plasma about $\{< t_{atom} > + < t_{ion} >\}^{-1} = \{(1 + K) < t_{atom} >\}^{-1}$ full cycles of preconditions of flashing LENR every second for each of the atoms (H or D) are possible.

These processes are shown in a symbolic form in Fig. 2.

4. Features and Efficiency of Nuclear Fusion Stimulated by Energy Fluctuations in Low-Temperature Magnetized Plasma

Let us briefly consider the features of the influence of such giant energy fluctuations on nuclear dd-fusion at a low mean plasma temperature.

The dynamics of $d\left(d, He^3\right)n, d(d,T)p$ reactions is described by the equations

$$\begin{aligned} \frac{dn_{He^3}}{dt} &= \frac{dn_n}{dt} = \eta n_d^2 {<}\sigma_{d+d=He^3+n} v{>}, \\ \frac{dn_t}{dt} &= \frac{dn_p}{dt} = \eta n_d^2 {<}\sigma_{d+d=t+p} \nu{>}. \end{aligned} \tag{20}$$

Here $\eta = P_{diss}\Delta t_{ion}^{(corr)} / (< t_{ion} > + < t_{atom} >)$ is the efficiency coefficient for the use of CCS in lowtemperature magnetic plasma; $P_{diss} \approx 1$ is the probability of dissociation of D_2 molecules into atoms in the considered range of plasma temperatures $kT \approx (2-4)\varepsilon_{diss}$.

The base expression for the average thermonuclear reaction rate at a specific plasma temperature has the following form

$$< \sigma_{fusion}(v) v >= \sqrt{\frac{8/\pi\mu}{(kT)^3}} \int_0^\infty \sigma(E) E e^{-E/kT} dE \tag{21}$$

and can be calculated taking into account the dependence of the same cross-section of both nuclear reactions on the speed of interacting particles [26-28]

$$\sigma_{fusion}(E) = \frac{S}{E} \exp\left(-\frac{\pi e^2 Z_1 Z_2}{\hbar}\sqrt{\frac{2\mu}{E}}\right) \tag{22}$$

Here μ is a reduced mass of interacting nuclei; T is the plasma temperature; $S = S_0\left(1 + a_1 T_9 + a_2 T_9^2 + a_3 T_9^3\right)$ is the astrophysical factor for dd-reactions; a_k are extrapolation parameters [28] corresponding to a specific reaction; T_9 is the plasma temperature, expressed in units of 10^9 K.

At low energy $S = S_0 \approx 56\mathrm{keV \cdot bn}$ and it significantly increases with the increase of energy (plasma temperature).

If we take into account the approximation $G(t) = G_{\max}\left|\sin\left(2\omega_H t\right)\right|$ presented in Fig. 1 and the replacement $T \to T_{eff}(t) = T\{G(t)\}^2$ then the formula for the thermonuclear reaction rate must be additionally averaged over time within the oscillation period $\pi/2\omega_H$

$$<< \sigma_{fusion}(v,t) v >>= \frac{2\omega_H}{\pi} \int_0^{\pi/2\omega_H} < \sigma_{fusion}(v, S(T(t))) v > dt \tag{23}$$

The results of such a double averaging of the thermonuclear interaction rate $\sigma_{fusion}(v,t)v$ for $d{+}d = t{+}p, He^3{+}n$ reactions are shown in Fig. 3. These graphs for both reactions visually coincide.

From these results it can be concluded that the maximum value of doubly averaged rate in the presence of correlation can reach a value $<< \sigma_{d+d}(v,t)v >> \approx 10^{-16}\ cm^3/sec$ at $T_9 = 10^{-4} (kT \approx 8.6 eV)$ and $G_{\max} \approx 300$. With such a value of doubly averaged rate, the final fusion efficiency is

$$\frac{dn_{fusion}}{dt} = n_d^2 \eta << \sigma_{d+d} v >> \approx 10^{16} - 10^{20}\ cm^{-3} \cdot sec^{-1} \tag{24}$$

at, respectively, the plasma density $n_d = 10^{14} - 10^{18}\ cm^{-3}$.

If we take into account that an energies of $\Delta E \approx 3.2 - 4 MeV$ are released in these reactions, then the maximal specific power of energy release can have a great value:

$$\frac{dn_{He^3}}{dt} \Delta E \approx 5\ kW - 50 MW/cm^3 \tag{25}$$

It should be noted that the actual power of energy release can be significantly lower due to the presence of negative feedback: a very fast and very significant increase in the local plasma temperature to the level $kT >> V_i$ leads to a

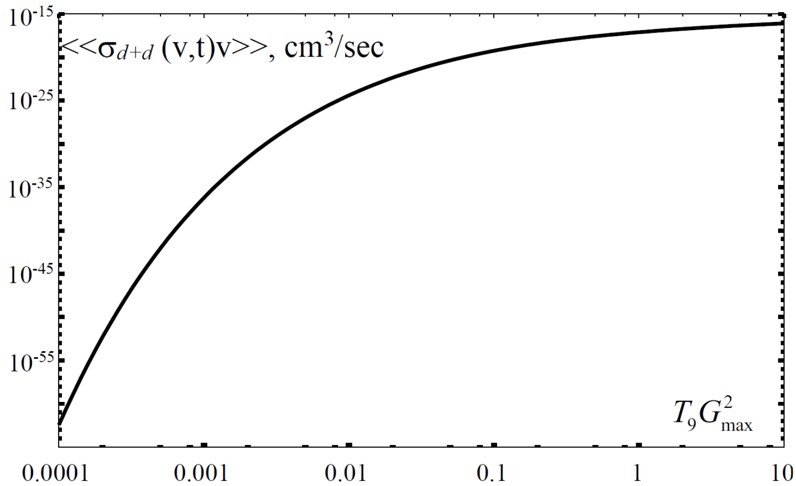

Figure 3. Dependence of the doubly averaged rate of thermonuclear interaction $<< \sigma_{fusion}(v,t)v >>$ for (d,d) reaction on the actual temperature and different maximum values $G_{\max}$ of the correlation efficiency coefficient.

slowdown in the process of ion recombination into the atomic state and, accordingly, to a decrease in the coefficient η in equations (20) and (24).

The subsequent cooling of the plasma accelerates nuclear fusion again. This is due to a very rapid increase in the intensity of the ultraviolet radiation of the heated plasma due to the Stefan-Boltzmann law $J_{rad} \approx \sigma T^4$, which leads to plasma cooling.

The combination of these processes automatically leads to a quasi-stationary regime of selfcontrolled nuclear fusion.

5. Conclusions

It is shown that taking into account of the microdynamic features of the processes of alternating ionization and recombination of hydrogen atoms and its isotopes in a magnetized low-temperature plasma makes it possible to implement the mechanism of self-controlled nuclear fusion using controlled very intense quasi-periodic fluctuations of the kinetic energy of these particles. The origin of these fluctuations is associated with the formation of coherent correlated states that are formed during each act of fast atom ionization.

A very important fact is that nuclear fusion in a low-temperature plasma can last an indefinitely long time and does not require large expenditures of energy.

Another very important advantage of CCS-based LENR reactions is connected with the possibility of a very significant increase in the pulsed effective temperature $T_i^* = \{G(t)\}^2 T_i$ with an average value $< T >_i^* = G_{\max}^2 T_i/2$, which can reach 30-100 keV and even more. This possibility makes realization of CCS stimulated fusion with the participation of heavier nuclei possible:

$$\begin{aligned} d + He^3 &= p + He^4 \\ d + Li^6 &= 2He^4 \\ p + Li^7 &= 2He^4 \\ p + B^{11} &= 3He^4, \ldots \end{aligned} \tag{26}$$

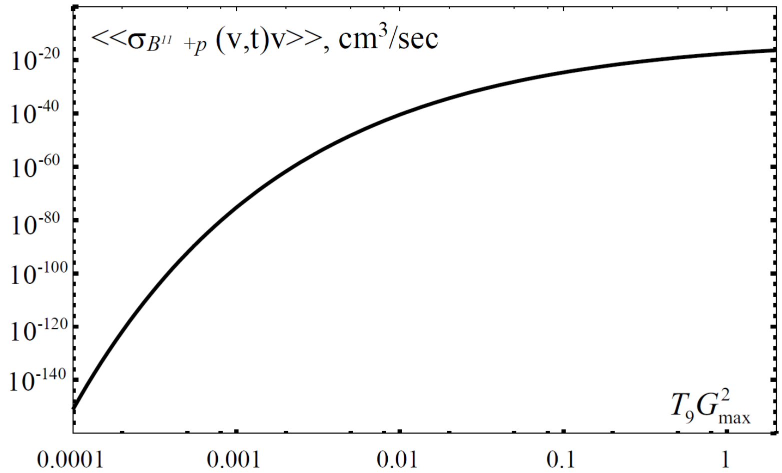

Figure 4. Dependence of the doubly averaged rate of thermonuclear interaction $<< \sigma_{B^{11}+p}(v,t)v >>$ for $\mathrm{B}^{11}\left(\mathrm{p},\mathrm{He}^4\right)2\mathrm{He}^4$ reaction on the actual temperature and different maximum values $G_{\max}$.

These heavier nuclei will be passive (not in the CCS state) targets in nuclear fusion and may be present in the hydrogen or deuterium plasma either as an admixture or as a result of previous nuclear reactions. The doubly averaged rate for $p + B^{11} = 3He^4$ reaction is presented in Fig. 4.

It can be seen from these data that the efficiency of this reaction in a magnetized low-temperature plasma in the presence of a CCS with large value of $G_{\max}$ is approximately the same as in $d + d = t + p, He^3 + n$ reactions.

The specificity and features of the implementation of LENR on the basis of the process of CCS formation in such reactions in different physical and biological systems are considered in [20], [29]–[30].

It should be noted that the optimum hydrogen plasma temperature for such the fusion is in the range of $10 - 20eV$. At a much higher temperature, the probability of ion recombination, which is necessary to start the next cycle of atomic transformations, is significantly suppressed. At a lower temperature (less than dissociation threshold energy of about $4.5eV$), the number of hydrogen molecules of the $H_2, HD, D_2, HT, DT, T_2$ type increases sharply, which do not provide an effective ionization recombination process with the alternation of a full cycle of switching on and off the charge of the particle (this is possible only for a hydrogen-like atom, but not for a molecule).

Estimates show that this optimal regime will be self-sustaining due to internal negative feedback that does not allow the temperature to rise above the optimal interval.

A very important and unique feature of the mechanism is the fact that it allows us to combine two mutually opposite requirements: a relatively low plasma temperature to ensure automatic frequent alternation of ionization and recombination, and the need for very high energy to ensure efficient nuclear fusion.

A more detailed analysis of the values and ratio of all characteristic times of each ionization and recombination cycle was carried out in [22-26, 31].

In conclusion, it should be noted, that the considered features of a self-sustaining LENR in a lowtemperature magnetized plasma will also be attained by the propagation of a correlated wave packet, the features of which were considered in [32-34].

The implementation of the considered fundamentally new mechanism of nuclear fusion at low temperatures [31] can be carried out both in an ordinary terrestrial laboratory and in also the atmosphere of the Sun and other stars, where all the necessary conditions are met.

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