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Research Article

A LENR Solution for Fundamental Mysteries of the Solar Corona (Anomalously High Temperature and Anomalous He^3 Concentration)

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Abstract

The features and the method for solving of two fundamental problems of astrophysics are considered: the anomalously high temperature of the solar corona above the surface of the Sun, which is 200 times higher than the temperature of the surface itself, as well as the anomalously high concentration of the He^3 isotope (compared to He^4) in this region. It is shown that both of these effects are associated with the implementation of LENR in a low-temperature magnetized plasma in the solar atmosphere due to the self-similar formation of coherent correlated states and the generation of giant particle energy fluctuations in this region.

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

1. Introdution

Among the fundamental mysteries of modern astrophysics and the Sun physics, one of the most mysterious is the problem of the anomalously high temperature of the solar corona surrounding the visible Sun surface (photosphere) with the temperature 5780 K. This temperature rises slowly as we move away from the surface towards the center of the Sun. It is logical to assume that as one moves away from the surface upwards, the temperature will decrease.

However, the actual situation appears to be just the opposite. Above the surface of the photosphere there is a thin (about 10^3 km) layer of the chromosphere, near the outer surface of which (at the bottom of the solar corona) the temperature increases to $(1.5–2)\cdot 10^6$K in the range of 100–300 km (Fig. 1). In this area concentration of particles is

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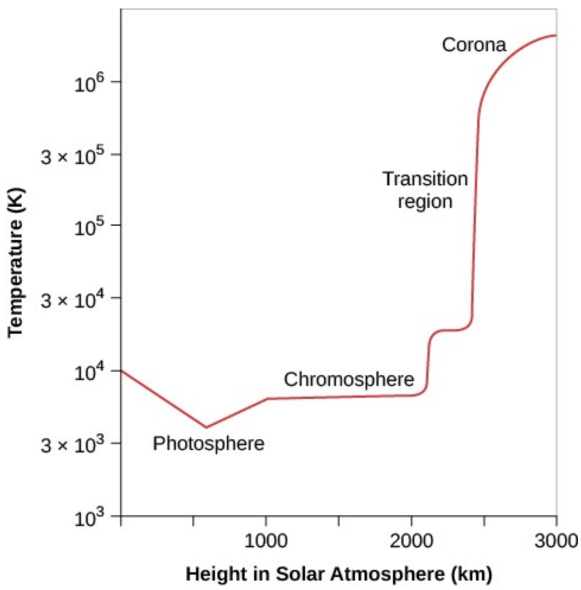

Figure 1. Altitude distribution of solar gas temperature in the lower part of the solar atmosphere [1].

about n≈10^8 cm^{-3}. In some places of this region the temperature rises to a value of $2 \cdot 10^7$ K, which is higher than in the center of the Sun.

Such features of temperature change contradict all the laws of thermodynamics.

All traditional (and unsuccessful) multiple attempts to explain these phenomena are associated with an unrealistic hypothesis about the possibility of "transit" ways of transferring energy without significant losses from the center of the Sun far beyond its surface through a much colder near-surface medium (e.g. [2]).

It has been shown that taking into account all possible "transit" mechanisms for heating the solar corona can provide no more than 3.5% of the corona energy that is recorded in numerous astronomical observations. Sources and mechanisms for the implementation of the rest of the energy are actually unknown. The greatest problem is the search for a mechanism that can stably maintain a high temperature of the corona throughout the entire solar cycle [3].

From numerous astronomical observations it is also well known that in this part of the Sun, very frequent vertical ejections of gas-plasma atom and ion magnetized substance (spicules of II type) occur from the volume of the photosphere, stimulated by fast switching (reconnections) of the magnetic field. These particles form a low-temperature plasma, which is held very firmly inside magnetic tubes and freely moves along its axis.

The process of formation of these open magnetic tubes occurs at the boundaries of photospheric supergranules of very large size, where there are opposite plasma flows, and concentrated extended zones of a strong magnetic field are generated. In these zones, the Kruscal-Schwarzshild instability conditions are satisfied [4], and the zone itself is divided into a system of magnetic tubes.

At any given time, there are about 10^6 such spicules on the Sun and they cover about 1% of Sun surface at any given moment of time. They move with an initial speed of $50-100$ km/s, have a diameter of 200–2000 km, an average lifetime of 5–7 min, and rise above the chromosphere to the lower part of the solar corona to a height of $(6-10) \cdot 10^3$ km. Inside the spicules, there is a circulating magnetic field $H \approx 2-3$kOe [5].

The plasma temperature in the observable part of the spicules, which exits the chromosphere, reaches $T \approx (1.5-2) \cdot 10^6$ K.

Figure 2. Photos of typical spicules on Sun surface [6], [7].

In some cases, the energy of vertical injection of such spicules is so high that these plasma flows overcome the gravitational field of the Sun and form coronal mass ejections into space, which, with the corresponding ejection direction, are registered on Earth and cause magnetic storms.

The typical photos of such spicules are presented in Fig. 2.

The scheme of magnetic field circulation and the direction of motion of the corresponding flows of low-temperature plasma forming spicules in the solar atmosphere (at the boundary of the photosphere, chromosphere and corona) are shown in Fig. 3.

The typical composition in the base of the spicule tube in photosphere is a “standard” low-temperature Sun gas (mainly hydrogen) with initial temperature $T \approx 10^4$ K and initial total hydrogen atom and ion concentration $n_{a0} \approx 10^{16} - 10^{17}\ \mathrm{cm}^{-3}$.

One of the hypothetical mechanisms of such a sharp heating is connected with the assumption of the possibility of inducing strong electric currents along very high circulating magnetic loops, vertical magnetic tubes with moving low-temperature plasma in the volume of solar spicules [7].

In this work, it is assumed that the presence of electrons in the volume of such a circulating field leads to the formation of a longitudinal electric current. It is also assumed that the collision of electrons and ions with neutral hydrogen atoms leads to a very strong heating of the moving solar gas to a temperature of $10^6 - 10^7$ K, which ultimately leads to anomalous heating of the solar corona. Such a mechanism does lead to an initial heating of the gas, but when it reaches temperature of 10–15 eV, the entire gas turns into plasma and the proposed heating mechanism becomes impossible. Based on this circumstance, it can be assumed that the initial heating of the gas can correspond to such

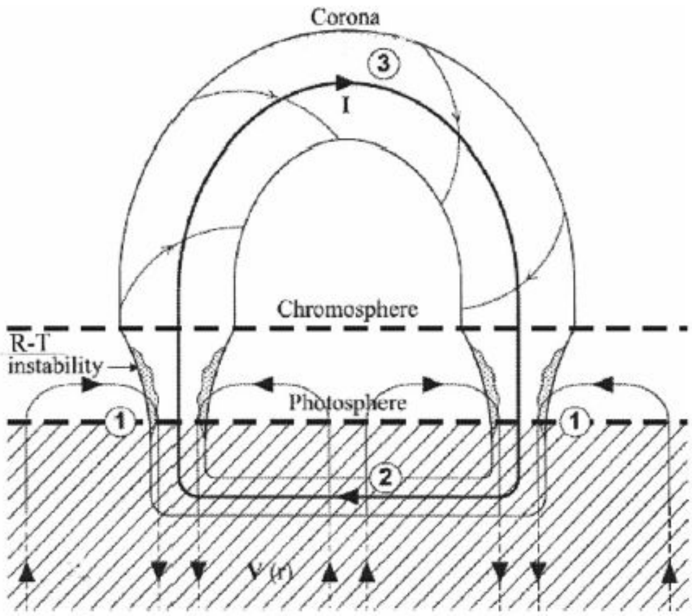

Figure 3. Scheme of spicule formation on the solar surface [8].

an electrodynamic mechanism up to a temperature of 3–5 eV, at which almost complete dissociation of hydrogen molecules occurs, but a significant part of neutral hydrogen atoms is retained. At the same time, the problem of the mechanism of further main heating of the solar gas (in fact, low-temperature plasma) to the observed high temperature of 200–2000 eV remains unresolved.

Another mystery is related to the anomalously high concentration of He^3 isotope (multiple times increase) relative to He^4 isotope in solar flares compared to the usual 0.0004 ratio. This result cannot be explained on the basis of the available data on processes on the Sun.

These anomalies are among main and fundamental problems of astrophysics.

An alternative method for solving this problem by implementing its own source of intense heating of the corona, which is not related to the transfer of heating energy from the central regions of the Sun, can be associated with the implementation of the mechanism of nuclear reactions directly in the volume of spicules. In this case, it would also be possible to find a solution to the problem of a high concentration of He^3 isotope.

Obviously, such a mechanism of self-heating of low energy matter due to the very low density of the medium and low temperature is not analogous to "standard" thermonuclear reactions, which take place, for example, in the center of the Sun. This conclusion is based on the traditional consideration of nuclear reactions under quasi-stationary conditions. An example of such a quasi-stationary system is plasma, which is usually characterized by averaged parameters that do not take into account the dynamic processes occurring at the nano-level.

The actual situation characterizing the features of nuclear interaction in locally dynamic systems is significantly different and much more optimistic. It is shown that such "nuclear solution" can be effectively implemented in low-temperature nuclear reactions optimized in self-similar process of formation of coherent correlated states of interacting particles [9]. The characteristic features of such states are the generation of giant fluctuations in the momentum and energy of these particles, which leads to a very significant increase in the cross section and the probability of nuclear reactions. It is shown below that this process and these mysteries can be successfully solved by LENR stimulated by the combined action of a constant magnetic field and spatial nanodynamics of low-temperature solar plasma.

2. Mechanism of the Formation of Coherent Correlated States of Protons and Deuterons in Stable Low Energy Solar Plasma

It is well known that the state of a charged particle in a magnetic field corresponds to a harmonic oscillator with a standard instantaneous spectrum of energy levels $E_n = \hbar\omega(n + 1/2), \omega = eH/M_i c$. In a plasma medium, the kinetic energy of such particles does not depend on the presence of an constant external magnetic field and is determined by the plasma temperature based on the relationship $\hbar\omega(n + 1/2) \approx kT$.

The quantum state of such an ion essentially depends on its environment.

In the idealized case of a single ion, the situation is rather simple. If, for example, an isolated charged particle began to interact with a magnetic field in time $t = 0$, then its state is determined by a coherent superposition of its own wave functions $\Psi_n(x)$ for each of two coordinates transverse to the direction of the magnetic field $\vec{H}$ with fixed initial phases $\varphi_n(0) = 0$ and deterministic change of these phases $\varphi_n(t) = E_n t/\hbar$ in time

$$\Psi(x) = \sum_n B_n \Psi_n(x) e^{-iE_n t/\hbar}, \Psi_n(x) = C_n H_n\left(x/x_0\right) e^{-x^2/2x_0^2},$$
$$C_n = \frac{1}{\sqrt{x_0 2^n n! \sqrt{\pi}}}, x_0 = \sqrt{\hbar/M\omega}, E_n = \hbar\omega(n + 1/2) \tag{1}$$

Here $H_n\left(x/x_0\right)$ is the Hermite polynomial.

In the optimal mode of switching on this interaction, the superposition of eigenfunctions forms a coherent correlated state (CCS) of the particle. The state of a particle in such a coherent superposition corresponds to Schrödinger-Robertson uncertainty relations [10]–[28]

$$\delta q \delta p \geq \hbar/2\sqrt{1 - r^2} \equiv \hbar^*/2,$$
$$\delta E \delta t \geq \hbar/2\sqrt{1 - r^2} \equiv \hbar^*/2,$$
$$\hbar^* = G\hbar, G = 1/\sqrt{1 - r^2} \tag{2}$$

with generation of giant fluctuations of the momentum and kinetic energy

$$\delta E_{G>1} = (\delta p)^2/2M \geq G^2\hbar^2/8M(\delta q)^2 = G^2 \delta E_{G=1} \tag{3}$$

of this particle.

Here $0 \leq r < 1$ and $1 \leq G < \infty$ are correlation coefficient and correlation efficiency coefficient.

Specific values of parameters r and G depend on the mode of switching on the interaction of the ion with the magnetic field from the initial value $\omega(0) = \omega_0$, which corresponds to the initial state of the atom based on the uncertainty relation, taking into account energy fluctuations, to the final value $\omega(t \to \infty) = \omega_0 g \equiv \omega_{\max} = eH/M_i c$ with a characteristic turn-on time equal to τ for different values $g = \omega_{\max}/\omega_0$ of the final change in the frequency

$$\omega(t) = \omega_0 \left\{1 + (g - 1)\left[1 - e^{-t/\tau}\right]\right\} \tag{4}$$

of the oscillator.

Here $g \approx 2\omega_i \sqrt{m_e/4\pi n_e e^2}$ is the coefficient of increase of the frequency of the magneticion oscillator during ionization of the atom, ω_i is the ionization frequency of the atom.

An analysis and direct calculation [11], [18], [22], [28] of the dynamics of the CCS formation process in such non-stationary systems show that the realistic value of the coefficient G for such a change of 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.

This lower limit corresponds to the case when the particle in effective harmonic oscillator was in the ground, lowest state with $E(0) = \hbar\omega/2$ before the switching on the interaction. In the case, when the initial state of the particle corresponded to the excited state of the oscillator with energy $E(n) = \hbar\omega(n + 1/2)$ the corresponding expression for the minimum energy of fluctuation has the following form [12], [13]

$$\delta E^{(\min)} = G^2 E(n) \tag{5}$$

This case, in particular, corresponds to the thermal energy of the medium with $E(n) = \hbar\omega(n + 1/2) \approx kT$, where such an oscillator is located, and leads to the following formula for effective thermal fluctuation

$$\delta T = G^2 T(n). \tag{6}$$

It is quite obvious that the realization of LENR in a low-temperature plasma using CCS in magnetic field is possible only during the single short time interval after CCS creation when there are large fluctuations of the kinetic energy of the particles. To repeat the considered process, it is necessary to turn off the interaction of a charged particle with a magnetic field, and then turn on such an interaction again. In laboratory conditions, such a repetitive process can be realized by frequently turning off and turning on the field.

It seems obvious that this is the only possibility for long-term quasi-stationary nuclear fusion. However, a more detailed analysis [9] shows that taking into account the nonstationary microdynamics of stationary plasma makes it possible to implement a fundamentally different process based on the natural switching on and off of the ion charge in a constant magnetic field. These processes are associated with alternating acts of ionization (charge switching on) of neutral hydrogen atoms or its isotopes and their subsequent recombination (charge switching off).

The analysis of these processes requires information on the composition and state of the gas-plasma medium.

Hydrogen atoms and ions ($\sim 94\%$) are the main elements of the solar atmosphere. To estimate the initial (molecular-atomic) state of hydrogen in the composition of solar gas, it is possible to use the Saha equation [29]–[32]

$$\frac{n_{a0}^2}{n_{m0} - n_{a0}/2} \approx 4\frac{(m_a kT/2)^{3/2}}{\hbar^3} \exp\left(-V_{diss}/kT\right) \tag{7}$$

interpreting it as an equation for determining the equilibrium ratio of the concentrations of hydrogen atoms n_a and molecules n_m taking into account the temperature and dissociation energy $V_{diss} \approx 4.5\text{eV}$ of hydrogen molecules.

A direct analysis of the solution of equation (7) at initial conditions $T = 10^4\ \text{K}(\text{kT} \approx 0.86\text{eV})$, $n_{m0} \approx 0.5 \cdot 10^{17}\ \text{cm}^{-3}$, shows that even at such a relatively low initial temperature, more than 99.99% of all hydrogen will be in a dissociated (non-molecular) state and $n_a \approx 2n_{m0}$. When the temperature increases, the probability of the existence of neutral molecules and molecular hydrogen ions becomes even less.

The subsequent analysis of the processes of ionization and recombination of hydrogen, as well as the processes of formation of coherent correlated states in the volume of magnetic tubes, will be carried out based on these results, assuming that the total concentration of hydrogen atoms and nuclei is equal to $n_{a0} \approx 2n_{m0}$. The equilibrium concentration of electrons and nuclei of the ionized part of atomic hydrogen at the beginning of the process of spicule formation (at $n_{a0} \approx 10^{17}\ \text{cm}^{-3}, T = 10^4$ K) can be determined using the standard form of the same Saha equation. Its solution has the following form:

$$\frac{n_{i,e}^2}{n_{a0} - n_{i,e}} \approx 4\frac{(m_a kT/2)^{3/2}}{\hbar^3} \exp\left(-V_i/kT\right) \equiv N_{i,e},$$
$$n_{i,e} = \sqrt{n_{a0}N_{i,e} + N_{i,e}^2/4} - N_{i,e}/2 \tag{8}$$

In this equations $V_i = 13.6\text{eV}$ is the ionization potential of a hydrogen atom; n_e, n_i and $n_a = n_{a0} - n_{e,i}$ are concentrations of electrons, hydrogen ions (proton or deuteron) and neutral atoms.

From this solution, using the given initial parameters, we find $n_{i,e} \approx 3 \cdot 10^{16}\ \text{cm}^{-3}$. As the temperature rises, the number of ions rapidly increases to a limiting value. It is very important that the state of a stationary plasma at the microlevel is non-stationary and is characterized by alternating ionization and recombination processes.

The corresponding durations of the existence of a neutral hydrogen atom before ionization $<t_{atom}>$ and an ion before recombination $<t_{ion}>$ are determined by the laws of plasma and are equal to:

$$<t_{atom}> = 1/<\sigma_{ion}(v_e)\,v_e>n_e = \left\{C_H n_e (kT_e)^{3/2}\sqrt{\frac{8}{\pi m_e}}\left(\frac{V_i}{kT_e}+2\right)\exp\left(-\frac{V_i}{kT_e}\right)\right\}^{-1}; \tag{9}$$

$$<t_{ion}> = n_i/n_a n_e <\sigma_{ion}(v)v_e> = K_{ia}<t_{atom}>$$

$$K_{ia} = \frac{n_{i,e}}{n_a} = \frac{n_{i,e}}{n_{a0}-n_{i,e}} \approx 4\frac{(m_e kT_e/2)^{3/2}}{\hbar^3 n_{i,e}}\exp\left(-V_i/kT_e\right). \tag{10}$$

In this equations $C_H \approx 6 \cdot 10^{-18}\ \text{cm}^2/\text{eV}$ is a parameter depending on the structure of the cross section $\sigma_{ion}(v_e)$ of the hydrogen ionization process [30], K_{ia} is the ionization parameter (the ratio of the concentrations of ions and non-ionized atoms in the solar low-temperature plasma).

It follows from (10) that for the initial stage of evolution of spicules (at $T = 10^4$ K and $n_{i,e} \approx 3 \cdot 10^{16}\ \text{cm}^{-3}$) we have $K_{ia} \approx 0.4$. For this stage

$$<t_{atom}> \approx 0.08\ \text{s}, <t_{ion}> \approx 0.03\ \text{s}. \tag{11}$$

As the temperature increases to $kT \approx 10 - 20\text{eV}$, the ion concentration increases to a maximum value $n_{e,i} \approx n_{a0}$, and the duration of alternating intervals decreases to values

$$<t_{atom}> \approx 10^{-8}\ \text{s}, <t_{ion}> \approx 0.01\ \text{s}. \tag{12}$$

With a subsequent increase in temperature, the value $<t_{atom}> \sim 1/(T_e)^{3/2}$ decreases indefinitely, while the duration $<t_{ion}>$ remains approximately the same.

3. Selective Low Energy Nuclar Fussin in Sun Spicules

The dynamics of possible thermonuclear fusion processes in spicule volume

$$\begin{aligned} \frac{dn_{He^3}}{dt} &= n_p n_d <\sigma_{p+d=He^3} v>, \\ \frac{dn_{H^3}}{dt} &= n_d n_d <\sigma_{d+d=H^3+p} v>, \\ \frac{dn_{He^3}}{dt} &= n_d n_d <\sigma_{d+d=He^3+n} v>. \end{aligned} \tag{13}$$

are based on the most effective reactions

$$p + d = He^3 + Q; d + d = He^3 + n + Q, H^3 + p + Q \tag{14}$$

involving deuterium.

The base formula for the average thermonuclear reaction rate at a specific plasma temperature has the standard form [34]–[36]

$$<\sigma_{fusion}(v)v> = \sqrt{\frac{8/\pi\mu}{(kT)^3}}\int_0^\infty \sigma_{fusion}(E)Ee^{-E/kT}dE \tag{15}$$

If we use the correct expression for the reaction cross section

$$\sigma_{fusion}(E) = \frac{S(E)}{E} \exp\left(-\frac{\pi e^2 Z_1 Z_2}{\hbar}\sqrt{\frac{2\mu}{E}}\right) \tag{16}$$

taking into account the astrophysical S-factor [34]–[36], then the final expression for the rate of thermonuclear interaction takes the form

$$\begin{aligned} &<\sigma_{fusion}(v)v> \equiv <\sigma_{fusion}(v)v>_v = Ae^{-B}\ \mathrm{cm}^3/\mathrm{s}; \\ &A \approx 1.3 \cdot 10^{-16} S\left(T_9\right)[\mathrm{keV}\cdot\mathrm{bn}]\left(Z_1 Z_2/\mu_A\right)^{1/3}/T_9^{2/3}; B \approx 4.246\left(Z_1^2 Z_2^2 \mu_A\right)^{1/3}/T_9^{1/3} \end{aligned} \tag{17}$$

Here $S\left(T_9\right) = S_0\left(1 + a_1 T_9 + a_2 T_9^2 + a_3 T_9^3\right)$ is astrophysical factor for dd-reactions; a_k are extrapolation parameters corresponding to a specific reaction [36]; Z_1, Z_2 are charges of interacting particles in units of proton charge; $\mu_A = A_1 A_2/\left(A_1 + A_2\right)$ is a reduced mass of interacting nuclei, expressed in mass numbers; T_9 is the plasma temperature, expressed in units of 10^9 K.

It follows from these results that in the case of standard solar plasma without CCS in the volume of lower part of spicules the rate of thermonuclear interaction for reactions (p,d) and (d,d) is very small $\sim 10^{-100}\ \mathrm{cm}^3/\mathrm{s}$. In this case any nuclear fusion is impossible.

A fundamentally different situation corresponds to the case when we take into account the real microdynamics of atoms in the volume of a magnetized plasma. In this case, the effective nonstationary temperature changes according to the replacement

$$T \to T_{eff}(t) = T\{G(t)\}^2. \tag{18}$$

At such approximation the basic formula (17) has the next form:

$$\begin{aligned} &<\sigma_{fusion}(v,t)v> = A^*(t)\exp\left\{-B^*(t)\right\}\mathrm{cm}^3/\mathrm{s}, \\ &A^* = A/G(t)^{4/3}, B^* = B/G(t)^{2/3}. \end{aligned} \tag{19}$$

In this case the final formula for the thermonuclear reaction rate has to be additionally averaged over time within the oscillation period $\pi/2\omega_H$

$$<<\sigma_{fusion}(v,t)v>> = \frac{2\omega_H}{\pi}\int_0^{\pi/2\omega_H} <\sigma_{fusion}\left(v, S\left(T_{eff}(t)\right)v\right> dt \tag{20}$$

In [9] it was shown that the formula $G(t) = G_{\max}\left|\sin\left(2\omega_H t\right)\right|$ is a very good approximation of the dependence $G(t)$ during the time interval of maintaining the coherence of the formed correlated state.

The results of such a double averaging (20) of the thermonuclear interaction rate $\sigma_{fusion}(v,t)v$ for (14) reactions with such approximation are shown in Fig. 4 for both low and high effective temperatures.

It is very important that the effective (virtual) temperature does not affect the quasistationary state of the plasma and the duration of the intervals of existence of ions $<t_{ion}>$ and neutrals $<t_{atom}>$, but it has a very significant effect on the probability of internuclear interaction.

In the idealized case such a regime can exist for an indefinitely long time. In a real material medium (in particular, in a gas or plasma), the optimal phase relationships are quickly violated due to collisions of an ion with other particles. In this case the duration of existence of such CCS with giant energy fluctuations δE is determined by the mean free path

$$\Delta t_{ion}^{(corr)} \approx <l>/<v_{ion}> \approx \sqrt{\left(kT_{ion}\right)^3 M_{ion}/4\pi n_i e^4 \Lambda} \tag{21}$$

of the ion in the plasma.

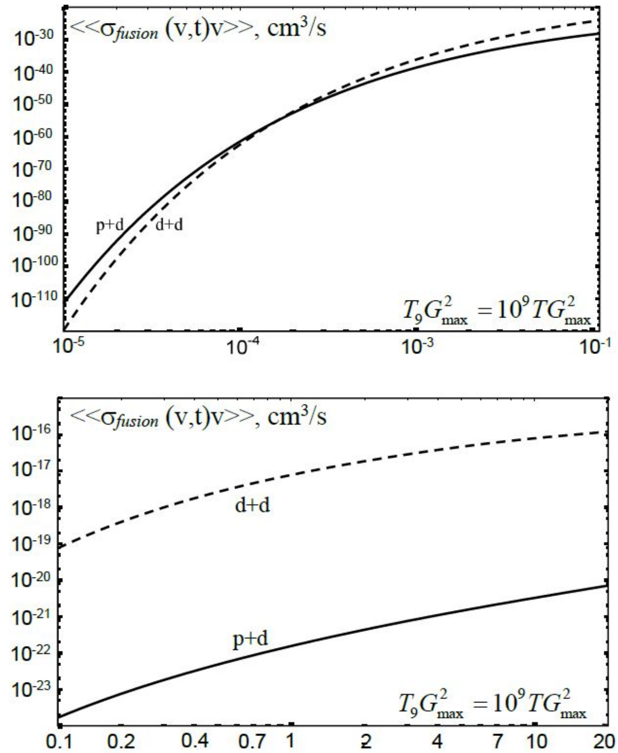

Figure 4. Dependence of double averaged thermonuclear interaction rate for (d,d) and (p,d) reactions in hydrogen low temperature plasma on the effective temperature and correlation coefficient.

The duration of the existence of such a correlated state with the accompanying giant fluctuations of the kinetic energy of a considered charged particles is equal to [30], [31]

$$\Delta t_{ion}^{(corr)} \approx <l>/v_i \approx \sqrt{(kT_i)^3 M_i}/4\pi n_i e^4 \Lambda. \tag{22}$$

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

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 calculate $\Delta t_{ion}^{(corr)}$ from formula (22) the replacement

$$T_i \rightarrow <T_i^{eff}(t)> = <G^2>_t T_i \tag{23}$$

should be made, which leads to a very significant increase of the lifetime $\Delta t_{ion}^{(corr)} \sim \left\{<G^2>_t\right\}^{3/2}$ of the CCS. In particular, for $kT_i = 1 - 10\mathrm{eV}$ and $n_i \approx 10^{17}\ \mathrm{cm}^{-3}$, the time $\Delta t_{ion}^{(corr)}$ increases from $\Delta t_{ion} \approx 10^{-9} - 10^{-12}$ s for the uncorrelated state to $\Delta t_{ion}^{(corr)} \approx 10^{-3} - 10^{-2}$ s for the values of $<G> \approx 200 - 1000$. This time is approximately equal to the time $<t_{ion}>$ of existence of the ionized state of an ion in a plasma and 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.

Taking these features into account leads to the following form of equations:

$$\frac{dn_{He^3}}{dt} = \left\{n_p^* n_d + n_p n_d^*\right\} <<\sigma_{p+d=He^3} v>>, \tag{24a}$$

$$\frac{dn_{H^3,p}}{dt} = n_d^* n_d <<\sigma_{d+d=H^3+p} v>>, \tag{24b}$$

$$\frac{dn_{He^3,n}}{dt} = n_d^* n_d <<\sigma_{d+d=He^3+n} v>>, \tag{24c}$$

which determine the dynamics of thermonuclear fusion processes in low energy magnetized plasma in spicule volume.

Here $n_{p,d}^* = \eta n_{p,d}; \eta = P_{diss}\ \Delta t_{ion}^{(corr)} / (<t_{ion}> + <t_{atom}>)$ is the efficiency factor for the use of CCS for nuclear fusion in flashing low-temperature magnetized plasma; $P_{diss} \approx 0.4 - 0.6$ is the probability of dissociation of hydrogen molecules or its isotopes into atoms in the considered range of temperature and plasma density; n_p^* and n_d^* are concentrations of protons and deuterons in correlated state.

From these equations, we can find the intensities

$$\frac{dn_{He^3}}{dt} \approx 1.5 \cdot 10^9 \text{ cm}^{-3} \text{ s}^{-1}, \tag{25a}$$

$$\frac{dn_{H^3,p}}{dt} \approx \frac{dn_{He^3,n}}{dt} \approx 1.9 \cdot 10^8 \text{ cm}^{-3} \text{ s}^{-1} \tag{25b}$$

of three considered nuclear fusion reactions for the real value $G_{\max} \approx 300 - 1000$ of the correlation efficiency coefficient and the initial concentrations $n_p(1-\eta) = 7 \cdot 10^{16} \text{ cm}^{-3}, n_p^* = 3 \cdot 10^{16} \text{ cm}^{-3}, n_d(1-\eta) = 2.1 \cdot 10^{12} \text{ cm}^{-3}, n_d^* = 9 \cdot 10^{11} \text{ cm}^{-3}$ of protons and deuterons in uncorrelated and correlated states.

The initial rate of average heating of each particle of the substance of spicules due to the energy of these reactions is equal to

$$\begin{aligned} &\frac{d(kT)}{dt} \frac{1}{n_i + n_e + (n_{a0} - n_{i,e})} \\ &\quad = \left\{\frac{dn_{He^3}}{dt} Q_{He^3} + \frac{dn_{H^3,p}}{dt} Q_{H^3+p} + \frac{dn_{He^3,n}}{dt} Q_{He^3+n}\right\} \frac{1}{n_{a0} + n_{i,e}} \approx 0.1 \text{eV/s} \end{aligned} \tag{26}$$

Such heating leads to an increase of the effective temperature $T_{eff} \sim T$, to an increase of the double averaged thermonuclear interaction rate $<<\sigma_{fusion}(v,t)v>>$, and to additional rapid ionization. In 15–20 seconds after the start of the process, the entire medium of the spicules becomes ionized, which leads to an increase of the concentration of CCS active protons n_p^* and deuterons n_d^* in the correlated state.

As a result of these processes, the intensities of fusion reactions increase to values

$$\frac{dn_{He^3}}{dt} \approx 10^{10} \text{ cm}^{-3} \text{ s}^{-1}, \tag{27a}$$

$$\frac{dn_{H^3,p}}{dt} \approx \frac{dn_{He^3,n}}{dt} \approx 6 \cdot 10^9 \text{ cm}^{-3} \text{ s}^{-1}, \tag{27b}$$

and the heating rate of each particle of the spicule substance increases to

$$\frac{d(kT)}{dt} \frac{1}{n_i + n_e} \approx 0.7 - 0.8 \text{eV/s} \tag{28}$$

It should be noted that fast neutrons and tritium H^3 isotopes formed in these reactions are also actively involved in subsequent nuclear fusion in a dense heated plasma. In particular, tritium nuclei are actively involved in the process of CCS formation with subsequent stimulation of a very efficient reaction

$$H^3 + d = He^4 + n + 17.589\mathrm{MeV}, \tag{29}$$

the probability of which is several orders of magnitude greater than that of the main reactions $\mathrm{d} + \mathrm{p}$ and $\mathrm{d} + \mathrm{d}$.

For this reason, the final concentration of tritium in the spicule plasma after its release into the solar atmosphere will be very low. From the photo (Fig. 2) it can be seen that the length L of the base of the spicules, located in the photosphere of the Sun, is approximately equal to the height of the magnetic loop itself and is equal to $6000 - 10000$ km. The plasma medium, under the action of the magnetic field of the tube, shakes the base of the spicule and begins to move vertically through the rest of the photosphere and the chromosphere, having a temperature of about $kT_L \approx 200\mathrm{eV}$.

Assuming the initial temperature $T_0 = 10^4$ K ($kT_0 \approx 0.86\mathrm{eV}$) and taking into account the almost linear law of the increase in plasma temperature with time, it is easy to determine that the translational velocity of deuterons during the time of movement at the base of the spicule increased from $v_{od} \approx 5$ km/s to $v_{Ld} \approx 70$ km/s. It follows from these data that the time of deuteron motion along the base of the spicule is equal to

$$\tau_{0L} \approx \frac{3L\sqrt{M_d}}{2\sqrt{2}} \frac{kT_L - kT_0}{(kT_L)^{3/2} - (kT_0)^{3/2}} \approx 3L/2v_{Ld} \approx 180 - 250\ \mathrm{s} \tag{30}$$

This result agrees well with the rate of specific heating of the spicule material (26) and with the final plasma temperature $kT_L \geq 200\mathrm{eV}$ at the end L of the horizontal part (base) of the spicule.

After changing the motion of the spicule from horizontal to vertical, it quickly passes (with little additional thermonuclear self-heating) through the thin layer of the chromosphere and moves with gravitational deceleration in the solar corona, effectively heating the surrounding atoms and ions. On this part of the trajectory, the transverse size of the magnetic tube with plasma increases rapidly, and the plasma density in the volume of the swelling spicules decreases to $n_{i,e} \approx 3 \cdot 10^9\ \mathrm{cm}^{-3}$ [37], and at an even higher height to $n_{i,e} \approx 10^8\ \mathrm{cm}^{-3}$. This process reduces greatly the probability of similar nuclear reactions taking place in the volume of the spicule on the outer part of the trajectory.

The discussed scenario for LENR realization due to the self-formation of CCSs makes it possible to substantiate the thermonuclear mechanism of giant and abnormal heating of the spicules and Sun atmosphere. An important factor is the complete synchronization of the observed heating of matter in the volume of spicules with the generation in this region of a very large amount of nuclear He^3 isotope, which is a daughter isotope of nuclear fusion reactions (14).

This result is a consequence of the specifics of the implementation of LENR and He^3 synthesis, taking into account the specifics of the formation of CCS in a low-temperature magnetized plasma for different particles:

- effective stimulation of (p, d) and (d, d) reactions, which lead to the formation of CCS and He^3 synthesis due to the alternation of complete ionization and recombination of hydrogen atoms;
- the impossibility of stimulation of similar low-energy nuclear reactions $He^3 + He^3 = 2p + He^4$ and $He^3 + He^4 = Be^7$, which can lead to a decrease in He^3 concentration, but correspond to a very low probability of CCS formation due to low probability of alternating full ionization (creation of He^3 nuclei) and full recombination (creation of neutral helium atoms).

The presence of such fundamental inequality of both types of nuclear reactions is the solution to the well-known He^3 problem: the presence of an excess amount of He^3 isotope in relation to He^4 in the composition of coronal ejections from the surface of the Sun. This problem cannot be solved on the basis of using the mechanism of standard thermonuclear fusion in the volume of stars due to the existence of alternative ways of creating and destroying of this isotope [9].

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