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NUCLEAR FUSION INDUCED BY A SUPER-INTENSE ULTRASHORT LASER PULSE IN THE DEUTERATED GLASS AEROGEL

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A SiO_2 aerogel with absorbed deuterium is proposed as a target for the fusion reaction $d+d \to He^3+n$ induced by a super-intense ultrashort laser pulse. The multiple inner ionization of oxygen and silicon atoms in the aerogel skeleton occurs in the super-intense laser field. All the forming free electrons are heated and removed from the aerogel skeleton by the laser field at the front edge of the laser pulse. The subsequent Coulomb explosion of the deuterated charged aerogel skeleton propels the deuterium ions up to kinetic energies of ten keV and higher. The neutron yield is estimated up to 10^5 neutrons per laser pulse during $\sim$ 200–500 ps if the peak intensity is 10^{18} W/cm^2 and the pulse duration is 35 fs.

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1. INTRODUCTION

A new laser technique with the generation of femtosecond super-intense pulses is a basis of new methods for the generation of neutrons. Several schemes have been suggested [1–5] with the usage of table-top lasers. Schwoerer et al. [5] demonstrated a two-step scheme of neutron generation. At the first stage, X-ray photons are emitted by a target irradiated by a super-intense laser pulse, and at the second stage, X-ray photons create neutrons as a result of the interaction with the nucleus Be^9. The approach of Ditmire et al. [1–4] used the fusion reaction between two deuterium nuclei (deuterons) that proceeds in accordance with the classical scheme

$$d + d \to He^3 + n.$$

In this method, large clusters of deuterium molecules are irradiated by a super-intense ultra-short laser pulse, and explosion of the produced positively charged clusters consisting of deuterons only leads to the formation of a plasma where the electrons and deuterons have the energy of several keV. The fusion reaction between deuterons proceeds both during the explosion of charged clusters and after their decay before the total plasma expansion out of the laser focal volume.

The neutron yield up to $n_n \sim 10^4$ neutrons per laser pulse was observed in experiments [3, 4] at the peak laser intensity $I \sim 10^{17}$ W/cm^2 and the pulse width 35 fs. For the laser focal volume V with the focal spot $2r = 200\mu$m and the length $l = 2$ mm [4], we have

$$V = 6.3 \cdot 10^{-5} \text{ cm}^3;$$

the number density of deuterons is then found to be

$$N_d = (2\text{–}3) \cdot 10^{19} \text{ cm}^{-3}.$$

Hence, the total number of deuterons in this plasma filament is of the order $n_d \sim 10^{15}$. Thus, only one of the $n_d/n_n = 10^{11}$ deuterons takes part in the nuclear fusion reaction! This extremely low efficiency is explained by a small tunneling rate constant of the fusion reaction and by a small lifetime of the forming plasma involving the deuteron filament ($\sim$ 200–500 ps).

The neutron yield could be increased by increasing the typical kinetic energy of deuterons, which is small

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compared to the classical threshold energy 180 keV of the fusion reaction involving two deuterons. In turn, the cluster expansion leads to the formation of fast deuterons under the action of the positive electric potential of the cluster consisting of deuterons. But there is an optimum cluster size for given parameters of the laser pulse. Indeed, a small cluster size leads to a small electric potential, and hence, to a small energy of deuterons in a plasma, whereas the laser signal cannot fully ionize a large deuterium cluster. In particular, under conditions of the experiments [3, 4], the optimum cluster radius is approximately $R \sim 25$ Å, which corresponds to the cluster charge $\sim +3000e$ after the field removal of all electrons and provides the typical kinetic energy of deuterons of several keV [6] (although the fusion reactions are mainly produced from clusters with the radii 80 Å and greater).

One can increase the typical deuteron kinetic energy by increasing the laser intensity. We now suggest an alternative approach where the aerogel with absorbed deuterium is used as a target for the laser irradiation instead of the deuterium cluster beam. The character of processes with the formation of fast deuterons is similar in both cases, but the aerogel method can provide a higher deuteron kinetic energy, in our opinion. In this paper, we analyze the processes resulting from the irradiation of a typical SiO_2 aerogel with absorbed deuterium by an ultra-short super-intense laser pulse.

2. PROPERTIES OF THE AEROGEL TARGET

We thus consider an aerogel with absorbed deuterium as a target for a power laser pulse. An aerogel can be described within a simple model where the aerogel matter consists of bound solid balls of identical radii a. These balls form a stable rigid skeleton due to contacts between the neighboring balls. At small distances from a ball, the aerogel has a fractal structure with the fractal dimension D. The aerogel matter is a homogeneous structure starting from a distance $R_c \gg a$ called the correlation radius. The aerogel consists of a fractal matter at distances $r < R_c$. These quantities are the basic aerogel parameters [7].

We note that the radius a of the individual ball is related to the specific internal aerogel surface S (which is usually measured in m^2/g) by [7]

$$S = \frac{3}{a\rho_0}, \qquad (1)$$

where ρ_0 is the (solid) mass density of the individual aerogel balls. Another relation between aerogel parameters that follows from its fractal structure is given by

$$\frac{\rho}{\rho_0} = \left(\frac{a}{R_c}\right)^{3-D}, \qquad (2)$$

where $\rho \ll \rho_0$ is the average aerogel mass density. For definiteness, we use the typical SiO_2 aerogel parameters [7] in what follows:

$$S = 715 \text{ m}^2/\text{g}, \quad \rho = 0.012 \text{ g/cm}^3, \quad D = 2.3.$$

Because the solid density of the SiO_2 aerogel material is $\rho_0 = 2.1$ g/cm^3, we obtain $a = 20$ Å from Eq. (1) and $R_c = 3\mu$m from Eq. (2).

We note that the maximum amount of absorbed deuterium matter obviously corresponds to its solid mass density $\rho_d = 0.17$ g/cm^3 inside the aerogel, because pores occupy the main part of the aerogel volume. The maximum amount of absorbed deuterium is therefore given by $\rho_d/\rho = 14$ g$_d$/g$_a$ (gram of deuterium matter per aerogel gram). However, the optimum amount of absorbed deuterium must be chosen at a much smaller value. We assume that the internal aerogel surface S can be covered by three deuterium layers. This assumption agrees with the surface laws in physical chemistry [8]. Because the average distance between deuterium molecules is 3.5 Å in solid deuterium matter, the thickness of deuterium matter is approximately equal to $l_d = 10.5$ Å on the surface of the aerogel. The amount of absorbed deuterium is then given by

$$\rho_d l_d S = 0.13 g_d/g_a \qquad (3)$$

and the laser radiation is mainly absorbed by the aerogel rather than deuterium. Each individual SiO_2 ball is covered by

$$n_0 = 4\pi\rho_d \frac{(l_d + a)^3 - a^3}{3M_d} = 2150$$

deuterium molecules. Here, $M_d = 6.7 \cdot 10^{-24}$ g is the mass of one deuterium molecule.

The individual aerogel elements can also be described by approximating these elements by cylindrical fibers that have common knots. In this model, the fiber radius a_f follows from the fractal approach relation (instead of Eq. (1)),

$$S = \frac{2}{a_f \rho_0}.$$

For the same specific area $S = 715$ m^2/g of the internal aerogel surface, we then obtain the value $a_f \approx 13$ Å. The amount of absorbed deuterium is given by the same expression (3). We assume that the average aerogel mass density is the same as in the ball model, i.e., $\rho = 0.012$ g/cm^3. Using Eq. (2), we find the correlation radius $R_c = 2.1\,\mu$m. The total length L of all the fibers in the plasma filament having the volume V is found from the relation

$$\rho_0 \pi a_f^2 L = \rho V.$$

This gives $L = 68$ km. We now estimate the total length l_c of all the fibers inside the correlation sphere with the radius R_c. We have the obvious relation

$$l_c = \frac{(4\pi R_c^3/3)}{V} L.$$

Inserting the above values of V, L, and R_c, we find that $l_c = 4.2$ cm.

We now estimate the average distance $\delta \gg a_f$ between the neighboring fibers in the correlation sphere. The average length of one fiber in this sphere is R_c. The quantity $\delta^2 R_c$ is the volume referring to one fiber in this sphere. The quantity

$$N_f = \frac{R_c^3}{\delta^2 R_c}$$

is the number of fibers in this sphere, and therefore, $l_c = R_c N_f$. We thus find

$$\delta = R_c \left(\frac{R_c}{l_c}\right)^{1/2} \approx 0.015\,\mu\text{m}.$$

In what follows, we consider the aerogel model consisting of the individual balls and cylindrical fibers.

3. AEROGEL IN A LASER FIELD

As a result of irradiating the aerogel by a super-intense ultra-short laser pulse, the following processes proceed. After a certain period of time, electrons are liberated from the aerogel skeleton by the laser field and occupy aerogel pores. The aerogel skeleton then consists of multicharged atomic ions of silicon and oxygen; deuterium nuclei (deuterons) are located on the internal skeleton surface. At the next evolution stage, all the atomic ions fly into the surrounding space forming a uniform plasma that fills all the aerogel space; deuterons fly first because they are light particles. They are located on the skeleton surface, and therefore, deuterons have the maximum kinetic energy.

The general character of the interaction of a power laser pulse with the aerogel system is similar to that for deuterium clusters. In what follows, we thus use the estimates that were obtained for the explosion of deuterium clusters under the action of a super-intense ultra-short laser pulse [6].

The mass of the individual SiO_2 ball is equal to

$$m = \rho_0 (4\pi a^3/3) = 7.0 \cdot 10^{-20} \text{ g}$$

and the SiO_2 molecule mass is $m_0 = 1.0 \cdot 10^{-22}$ g. The number density of SiO_2 molecules in the ball is

$$N_0 = \frac{\rho_0}{m_0} = 2.1 \cdot 10^{22} \text{ cm}^{-3}.$$

Hence, one ball contains approximately $n = m/m_0 = 700$ SiO_2 molecules, and $n_0 = 2150$ deuterium molecules are located on its surface (see the previous section). We assume that the laser peak intensity is $I_{max} = 10^{18}$ W/cm^2, the laser wavelength is $\lambda = 800$ nm, and the pulse width is $\tau = 35$ fs (defined as the full width at the half maximum, see [9]). The laser field strength $F(t)$ is then defined as

$$F(t) = F_{max} \exp[-(t/30)^2]$$

(which t measured in fs) and the peak laser field strength is $F_{max} = 5.25$ a.u. (the linear polarization of the laser field is considered; the atomic units correspond to $e = m_e = \hbar = 1$). The laser focal volume is equal to $V = 6.3 \cdot 10^{-5}$ cm^3 (see the Introduction). The mass of the aerogel in this volume is

$$M = \rho V = 7.6 \cdot 10^{-7} \text{ g}.$$

Hence, the number of the aerogel solid balls in the plasma filament can be estimated as

$$n_b = M/m = 1.1 \cdot 10^{13}.$$

4. INNER AND OUTER IONIZATION OF THE AEROGEL

We now consider the processes that occur during the interaction of laser light with the aerogel. A multiple inner ionization of silicon, oxygen, and deuterium atoms first occurs in this laser field (of course, the molecular bonds are destroyed very quickly). Taking the known values of the ionization potentials E_Z of multicharged Si and O atomic ions into account (where Z is the charge multiplicity of the respective atomic ion), we find that the above-barrier inner multiple field ionization occurs in the laser field when the Bethe condition is satisfied [10]:

$$F(t) > \frac{E_Z^2}{4Z}. \quad (4)$$

Here, $F(t)$ is the amplitude of the laser field strength at the time moment t.

Using the known values of the ionization potentials of atomic ions [11], we find from Eq. (4) that at the leading edge of the laser pulse, the charge multiplicity is $Z = 6$ for oxygen atomic ions. Each oxygen atomic ion preserves only two electrons of the K-shell because the K-shell ionization potentials are very high, 739 and 871 eV, respectively. Further, $Z = 9$ for silicon atomic ions, which means that each Si atomic ion preserves only two K-shell electrons and three L-shell electrons. The ionization potential of the Si atomic ion with $Z = 9$ is equal to 401 eV, and this quantity does not satisfy condition (4) even at $F(t) = F_{max}$.

We thus conclude that $9 + 2 \times 6 = 21$ electrons are removed at the leading edge of the laser pulse from each SiO_2 molecule inside the individual ball during the inner atomic ionization process. We neglect the quantum-mechanical tunneling atomic ionization at the start of the laser pulse because its probability is too small compared to the probability of the classical above-barrier ionization [12]. Therefore, each individual ball contains

$$n_e = 21 \times n + 2n_0 = 14700 + 4300 = 19000$$

free electrons after irradiation by the laser pulse (here, we also accounted for two electrons ejected from each deuterium molecule on the surface of the individual aerogel ball).

Simultaneously, the outer above-barrier ionization proceeds at the leading edge of the laser pulse, which means that the electrons leave the individual aerogel ball. We can calculate the number Q of electrons removed from the ball by the laser field by applying the Bethe model again. Instead of Eq. (4), we have a similar condition based on the Coulomb binding potential E_Q for electrons in the individual ball with the positive charge Q; for $Q \gg 1$, the potential is given by $E_Q = Q/a$, and therefore (see the review paper [13] for details),

$$F(t) > \frac{Q}{4a^2}. \tag{5}$$

The thermal mechanism of the outer ionization for femtosecond time range and for moderate dimensions of the individual aerogel balls gives an additional contribution (see estimates in [14] and the discussion below). The amplitude of electron oscillations in the laser field is

$$a_0 = F_{max}/\omega^2 = 860\ \text{Å} \gg a,$$

and therefore, the electrons do not return to the individual ball after such oscillations with high probability.

We note that Eq. (5) for the outer ionization is not so obvious as Eq. (4) for the inner ionization. The relation $E_Q = Q/a$ becomes invalid when a few electrons remain in the center of the ball. Assuming that positive atomic ions are homogeneously distributed in the ball, we find that $E_Q = 3Q/2a$. Finally, if the stronger inequality $F(t) > Q/a^2$ is satisfied (the laser force is stronger than the Coulomb force), then electrons are definitely removed from the individual aerogel ball.

We now evaluate the number of electrons Q that are released from an aerogel ball under the action of the laser field. From Eq. (5), we obtain $Q = 30000$ released electrons for $F(t) = F_{max}$; this means that all the $n_e = 19000$ free electrons are liberated in the outer ionization from each aerogel ball at the leading edge of the laser pulse. These free electrons are then uniformly distributed in the plasma filament. The total number of free electrons in the plasma filament is equal to

$$n_t = n_e n_b = 2.1 \cdot 10^{17}.$$

The concentration of these free electrons in the plasma filament is estimated as

$$N_e = n_t/V = 3.3 \cdot 10^{21}\ \text{cm}^{-3}.$$

Free electrons inside the individual ball are heated during the laser pulse. First, each electron acquires a large kinetic energy equal to the average oscillation energy $F^2/4\omega^2$. This quiver energy is equal to 58 keV for the peak intensity $I = I_{max}$. However, after the end of the laser pulse, the electron looses all its quiver energy, because the kinetic energy of the electron adiabatically follows the envelope of the laser pulse. According to Ref. [12] in the case of the above-barrier ionization, the final kinetic energy of electrons is of the order 10–20 eV only. Indeed, for the above-barrier ionization (and also for the tunneling ionization), the real energy spectrum of electrons is determined by the simple exponential law [12]

$$w(E) \propto \exp\left(-\frac{2E_e\gamma^3}{3\omega}\right), \quad \gamma = \omega\sqrt{\frac{8a}{F(t)}}. \tag{6}$$

The quantity

$$\gamma = \frac{\omega\sqrt{2E_Q}}{F(t)}$$

is the so-called Keldysh parameter (see Ref. [12] for details) for the ejection of electrons from the individual ball by the laser field. For the maximum value $F = 5.25$ a.u., we obtain from Eq. (6) that $\gamma = 0.4$. Because $\gamma < 1$, we find that the above-barrier outer ionization by a quasistatic laser field is indeed realized.

It then follows from Eq. (6) that the typical electron kinetic energy is

$$E_e \approx \frac{3\omega}{2\gamma^3} \approx 35 \text{ eV}.$$

Therefore, free electrons remain quite cold immediately after the outer ionization. But then free electrons can again significantly increase their kinetic energy in the ball expansion process. The Coulomb potential energy of electrons is transformed into their kinetic energy [6]. As a result, the electron temperature increases up to the final value $T_e \sim 1$ keV. In addition to this, the induced inverse bremsstrahlung [14, 15] in the plasma filament can contribute to the increase of the electron kinetic energy when electrons are scattered by the charged individual balls before the laser pulse depletes. The amount of this contribution is unclear because of quick expansion of these balls.

We note that the Coulomb expansion of an individual ball proceeds slowly in comparison with the electron release; therefore, it is insignificant during the process of the outer field ionization. Indeed, the time t for doubling the ball radius can be estimated from a simple energy balance for the silicon atomic ion at the ball surface (see Ref. [15] for details),

$$\frac{(Q/2)}{a} - \frac{(Q/2)}{2a} = \frac{1}{2}M_0 v^2 = \frac{1}{2}M_0\left(\frac{2a}{t}\right)^2,$$

where M_0 is the mass of a single silicon atomic ion and v is its velocity at the time instance t. In this estimate, we used the typical time instance when a half of the free electrons $(Q/2)$ are removed from an individual ball. It follows from this relation that the ball radius a is doubled during the time

$$t = \sqrt{\frac{8M_0 a^3}{Q}} = 20 \text{ fs}. \qquad (7)$$

Hence, we can neglect the expansion of the individual ball before the total ejection of all the $Q = 30000$ electrons from an individual ball at the leading edge of the ultrashort laser pulse. Estimates for the oxygen atomic ion lead to a similar conclusion.

The laser energy is absorbed by free electrons in the plasma filament. In accordance with Eq. (6), each electron acquires the energy $E_e \approx 35$ eV from the laser field (another part of the electron energy ~ 1 keV is acquired from the Coulomb potential energy of the electrons in the ball). If the laser energy in the pulse is, e.g., $E = 1\text{J} = 6.2 \cdot 10^{18}$ eV, it follows that $n_l = E/E_e = 1.8 \cdot 10^{17}$ electrons absorb the entire energy of the laser pulse. But we have found above that the total number of free electrons in the plasma filament is $n_t = 2.1 \cdot 10^{17}$, which is approximately equal to n_l. Thus, we conclude that for the high-intensity laser field, a low-frequency electromagnetic wave penetrates into the entire plasma filament.

The analysis leads to the following conclusions. First, a standard concept that the electromagnetic wave with the frequency $\omega < \omega_p$ cannot propagate in a plasma (see, e.g., [16]) is not valid at a high intensity of the electromagnetic field. Second, the propagation of a strong electromagnetic wave causes a redistribution of plasma charges, and the interaction of the electromagnetic wave with a forming non-uniform plasma may be important for plasma heating. We note that we neglected this interaction in the above analysis, and formation of the plasma under the action of the electromagnetic wave results only in the separation of electrons and ions of the aerogel skeleton by the wave. A partial absorption of the electromagnetic wave by a forming plasma as a result of collective excitations in this plasma may contribute an additional heating of the plasma.

Deep penetration of the ultrahigh-intensity laser pulse into a dense plasma is also confirmed by theoretical results in Ref. [17].

5. FUSION PROCESSES

We finally estimate the number of fusion neutrons produced in the plasma after the end of the laser pulse. During the preliminary diffusion of the deuterium gas through the aerogel, the deuterium molecules penetrate inside the pores of the aerogel; then they adhere to the surface of individual balls. Of course, large pores in the fractal structure of the aerogel allow several layers of deuterium molecules to cover each of the SiO_2 balls. We estimated above that $n_0 \sim 2150$ deuterium molecules adhere to each SiO_2 ball surface. This estimate corresponds to three layers of deuterium molecules at the ball surface with the radius $a = 20$ Å. Deuterons are attracted to the free ends of the oxygen radicals. It must be noted that it is probably better to use heavy water instead of the deuterium gas, because the polar D_2O molecule is better attached to the skeleton surface than the nonpolar D_2 molecule.

We now derive the number density of deuterons in the laser focal volume V:

$$N_d = \frac{2n_0 n_b}{V} = 7.5 \cdot 10^{20} \text{ cm}^{-3}.$$

It is by ten times greater than in experiments [1–4] with deuterium clusters (see the Introduction).

At the Coulomb explosion of the individual aerogel balls, each deuteron acquires the maximum kinetic energy

$$\frac{Q}{a+l_d} = 13.5 \text{ keV}.$$

We note that the hydrodynamic expansion of the ball with the ion sound velocity is negligibly small compared to the Coulomb expansion, in contrast to the expansion of large Xe clusters [15].

We now consider the Coulomb explosion in the model of cylindrical fibers. The number density of SiO_2 molecules in the solid fiber matter (see above) is $N_0 = 2.1 \cdot 10^{22}$ cm^{-3}. After the inner ionization, the unit of the fiber length contains the electric charge

$$Z = 21 N_0 \pi a_f^2 = 2.3 \cdot 10^{10} \ e/\text{cm}.$$

According to the Gauss electrostatic theorem, the electric field strength $F(r)$ at the distance r from the fiber axis is found from the relation

$$2\pi r F(r) = 4\pi Z.$$

On the surface of the fiber, the field strength is

$$F_0 = F(a_f) = \frac{2Z}{a_f} = 10.\dot{0} \text{ a.e.}$$

Hence, the difference of electric potentials between the surface of the given fiber and the neighboring fiber is

$$\Delta\varphi = F_0 a_f \ln(\delta/a_f) = 16 \text{ keV}.$$

This quantity is equal to the maximum kinetic energy of the deuteron. It is seen that the models of fibers and of balls give similar values of the deuteron kinetic energy.

The cross-section of the fusion reaction

$$d + d \to {}^3\text{He} + n$$

is $\sigma = 10^{-30}$ cm^2 for the deuteron kinetic energy $E_d = 10$ keV [18] (the reaction $d + d \to t + p$ has the same cross-section, but we are not interested in this reaction channel here). The rate for this nuclear reaction is $w = \sigma N_d v$, where v is the deuteron velocity. The time for the nuclear fusion is determined by the flight time T of the deuteron from the axis of the laser focal volume to its radial boundary, i.e., $T = r/v$. Hence, each deuteron produces

$$wT = \sigma N_d r = 7.5 \cdot 10^{-12} \ll 1 \text{ neutrons}$$

at the collisions with other deuterons. The total yield of neutrons n_n per laser pulse can be obtained by multiplying this quantity with the number $n_d = n_0 n_b$ of deuteron pairs in the laser focal volume:

$$n_n = wT n_0 n_b \approx 10^5.$$

These estimates refer to the ball model of aerogel.

We now make a similar estimates in the fiber model of aerogel. If the quantity $S = 715$ m^2/g is the specific area of the aerogel (Sec. 2) and $M = \rho V$ is the mass of the aerogel ($\rho = 0.012$ g/cm^3 is the mass density of the aerogel and V is the volume of the plasma filament), then the quantity MS is the total area of the aerogel in the plasma filament. This area is covered by three layers of deuterium molecules. The thickness of this layer is $l_d = 10.5$ Å (Sec. 2). Hence, the quantity MSl_d is the volume of the deuterium layer and the quantity $\rho_d MSl_d$ is its mass ($\rho_d = 0.17$ g/cm^3 is the mass density of the solid deuterium matter). The number of deuterium molecules in the plasma filament is

$$n_d = \frac{\rho_d MSl_d}{M_d}$$

($M_d = 6.7 \cdot 10^{-24}$ g is the mass of one deuterium molecule). Thus, the number density of deuterons in the plasma filament is

$$N_d = \frac{n_d}{V} = \frac{\rho_d \rho S l_d}{M_d} = 4.6 \cdot 10^{20} \text{ cm}^{-3}.$$

It is seen that this estimate is nearly the same as the corresponding estimate in the ball model of aerogel (see above). Hence, the estimate of n_n is also the same as above.

It should be noted that the cross-section σ increases by several decimal orders compared to the case of the experiments of Ditmire et al. [1–4] with deuterium clusters, and the number of deuterons in the plasma filament $2n_0 n_b = 4.7 \cdot 10^{16}$ is larger than the number of deuterons $n_d \approx (2\text{–}3) \cdot 10^{15}$ (see the Introduction) in the plasma filament of the same dimensions used in the experiments [1–4]. Nevertheless, the neutron yield increases by only ten times. In our opinion, the reason is that in the experiments of Ditmire et al., only deuterons with large radii $R \approx 80$ Å take part in the nuclear fusion, while in our approach, the radius of the individual aerogel ball is only $a = 20$ Å.

We can conclude that the yield of neutrons is greater by approximately ten times compared to the yield of neutrons at the irradiation of deuterium clusters by super-intense ultrashort laser pulse observed in the experiments [1–4] (see also recent theoretical calculations for deuterated clusters in Ref. [19]). Thus, an aerogel saturated by deuterium can be used for the production of powerful sources of ultrashort pulses (about $T = 200$–500 ps) of monochromatic neutrons (2.45 MeV).

6. CONCLUSION

Developing the method by Ditmire et al. [3, 4] for the production of neutrons under the action of a super-intense ultrashort laser pulse, we propose to use the aerogel skeleton with absorbed deuterium instead of the deuterium cluster in the experiments by Ditmire et al. This allows increasing the neutron yield per laser pulse by one order of magnitude because of a higher kinetic energy of deuterons liberated at the Coulomb explosion of the charged aerogel skeleton. It should be noted that an interesting theoretical approach was recently proposed in Ref. [20]: it is suggested to use heteronuclear clusters containing deuterium, e.g., clusters from D_2O molecules.

It is possible that the tungsten aerogel [21] has an advantage compared to the SiO_2 aerogel considered in our paper, due to a high charge of the tungsten nucleus.

We note in conclusion that the Lawson criterion is $\sim 10^{-5}$ for deuterium clusters and $\sim 10^{-4}$–10^{-3} for the aerogel. The proposed method can be discussed as a version for the basis of the laser thermonuclear reactor.

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