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GENERATION OF NEUTRONS AT THE RELAXATION OF FAST DEUTERONS IN DEUTERIUM MATTER

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We analyze the fusion process involving two deuterium nuclei in the case of deceleration of a fast deuteron with the energy of approximately 100 keV located in a deuterium target. We calculate the probability $w_{fus}(\varepsilon)$ to generate a neutron by a fast deuteron with an initial kinetic energy ε during its deceleration. The mean free path of fast deuterons with respect to their relaxation is found for various deuterium targets. The data are analyzed for neutron generation in deuterium cluster beams at laser irradiation. The method of neutron generation at the collision of two deuterium cluster beams is suggested.

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1. INTRODUCTION

In a fusion reactor, formation of neutrons as a result of interaction between deuterium or tritium nuclei proceeds in a stationary regime, when these nuclei can be located in a plasma for a sufficiently long time. Then a test nucleon, exchanging energy with other ones, may finally partake in the fusion reaction. Then the Lawson criterion is fulfilled, and the probability for the test deuteron to react exceeds the one during its location in the thermonuclear plasma.

Different conditions occur when fast nuclei formed as a result of a pulsed excitation of a thermonuclear matter can react in the course of their braking. Because the relaxation rate for fast nuclei is higher than the rate of the thermonuclear reaction, the probability for fast nuclei to partake in the thermonuclear reaction is small and the Lawson criterion is not fulfilled. It is therefore impossible to construct a thermonuclear reactor in the framework of this scheme. Nevertheless, a pulse method of formation of fast nuclei can be a basis for a neutron generator. This method was used in experiments with femtosecond laser excitation of deuterium nuclei that are subsequently decelerated in a deuterium-containing target (films, liquid drops, clusters) and cause a fusion reaction with a neutron released (see, e.g., [1–5]). The first stage of laser excitation is the formation of fast deuterium ions, which subsequently collide with slow deuterons or deuterium-containing molecules. Below, we analyze peculiarities of this scheme of neutron generation as a result of relaxation of fast deuterium nuclei in a deuterium-containing matter.

In the analysis of this scheme, we restrict ourselves to the case of deuterium, because tritium radioactivity leads to additional requirements that complicate the general scheme. In this scheme, neutrons can be produced in the fusion reaction

$$d + d \to {}^3\mathrm{He}(0.82\ \mathrm{MeV}) + n\ (2.45\ \mathrm{MeV}), \qquad (1)$$

where fast deuterium nuclei (deuterons) have energies of several tens of keV. The deuterium target may be in the form of a solid deuterium foil, deuterium clusters or a deuterium gas, and a fast deuterium beam consists of individual deuterons or deuterium clusters.

In considering propagation of fast deuterons or deuterium clusters through a dense deuterium target,

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we have two mechanisms describing relaxation of fast deuterons: by excitation of electrons in this matter and by elastic scattering on nuclei. A typical excitation energy in the first mechanism is of the order of 10 eV per electron (a typical atomic energy); we neglect the electron mechanism of the energy loss for fast nuclei when the kinetic energy of deuterons is tens of keV. Thus, deceleration of fast deuterons in a deuterium matter results in the Coulomb scattering of fast deuterons on slow deuterium molecules. We note that our consideration is restricted to only a pure deuterium matter. We also neglect the Coulomb decay of a deuteron into a proton and a neutron because of the large binding energy of a deuteron (2.24 MeV).

In this paper, we are also guided by laser excitation of deuterium cluster beams because of numerous experimental studies of this process during the last decade.

2. GENERAL PECULIARITIES OF THE RELAXATION OF FAST DEUTERONS IN DEUTERIUM TARGETS

We analyze the stopping of fast deuterons in a deuterium matter and derive the probability w_{fus} that they take part in fusion reaction (1) during the deuteron deceleration. This probability is given by

$$w_{fus} = \int_0^{\varepsilon} N_i v \sigma_{fus} \frac{d\varepsilon}{d\varepsilon/dt}, \tag{2}$$

where $d\varepsilon/dt$ is the stopping rate (reaction (1) is weak and does not make a contribution to the stopping rate), N_i is the number density of target nuclei, σ_{fus} is the fusion cross section of reaction (1), and v is the velocity of the fast deuteron.

Because the energy of a fast deuteron significantly exceeds a typical atomic energy, a significant scattering occurs when the distance between atomic particles is small compared with the Bohr radius a_0. Hence, the pair collisions occur via the Coulomb interaction between colliding particles. In this case, the cross section of scattering with the loss of energy $\Delta\varepsilon$ by the fast deuteron is given by the Rutherford formula [6]

$$d\sigma = \frac{\pi Z_1^2 Z_2^2 e^4}{\varepsilon(\Delta\varepsilon)^2}\, d\Delta\varepsilon, \tag{3}$$

where ε is the kinetic energy of the fast deuteron and Z_1 and Z_2 are charge multiplicities of the colliding nuclei. From this expression, we obtain the fast deuteron braking rate [7] taking the deuteron charge multiplicity to be $Z_1 = 1$ and the charge of a scattered nucleus to be $Z_2 = Z$:

$$\frac{d\varepsilon}{dt} = \int (\varepsilon - \varepsilon') N_i v d\sigma(\varepsilon \to \varepsilon') = N_i v \frac{\pi Z^2 e^4}{\varepsilon} \times \\ \times \int \frac{d\Delta\varepsilon}{\Delta\varepsilon} = N_i v \frac{\pi Z^2 e^4}{\varepsilon} \ln\left(\frac{\Delta\varepsilon_{max}}{\Delta\varepsilon_{min}}\right), \tag{4}$$

where ε and ε' are energies of the fast deuteron before and after the collision, and the energy loss $\Delta\varepsilon = \varepsilon - \varepsilon'$ is small compared with the deuteron energy ε. Evidently, by an order of magnitude, the maximum energy loss is $\Delta\varepsilon_{max} \sim \varepsilon$, and the minimum energy loss corresponds to the impact parameter of the order of the atomic size a_0 for a dense deuterium target. Then the minimum energy change is

$$\Delta\varepsilon_{min} \approx \frac{Z^2 e^4}{a_0^2 \varepsilon}.$$

In particular, for the deuteron energy $\varepsilon = 100$ keV, the minimum energy loss at the scattering on a bound nucleus is $\varepsilon_{min} \approx 3 \cdot 10^{-4}$ eV. Correspondingly, Eq. (4) reduces to the form [7]

$$\frac{d\varepsilon}{dt} = 2 N_i v \frac{\pi Z^2 e^4}{\varepsilon} \ln\Lambda, \tag{5}$$

where we define the Coulomb logarithm

$$\ln\Lambda = 2\ln\left(\frac{\varepsilon a_0}{Z e^2}\right).$$

In particular, for $\varepsilon = 100$ keV, we obtain $\ln\Lambda \approx 15$. This value of the Coulomb logarithm is used in the subsequent derivations.

Substituting Eq. (5) in Eq. (2) and taking $Z_1 = 1$, we find the probability of neutron generation in the course of braking of an individual deuteron with the initial energy ε_0:

$$w_{fus}(\varepsilon_0) = \int_0^{\varepsilon_0} \frac{\sigma_{fus}(\varepsilon)\varepsilon d\varepsilon}{\pi Z^2 e^4 \ln\Lambda}. \tag{6}$$

Here, Z is the average charge multiplicity of target ions. Assuming the fusion cross section σ_{fus} to be strongly dependent on the fast deuteron energy ε, we can simplify Eq. (6) to

$$w_{fus} = \frac{\sigma_{fus}(\varepsilon)\varepsilon\Delta\varepsilon}{2\pi Z^2 e^4 \ln\Lambda}, \quad \Delta\varepsilon = \left(\frac{d\ln\sigma_{fus}}{d\varepsilon}\right)^{-1}. \tag{7}$$

Guided by the collision energies ranging from 20 keV to 200 keV for a fast deuteron, we use the data in [8] for the fusion cross section $\sigma_{fus}(\varepsilon)$. The measured cross sections of reaction (1) are approximated by the following formula in the range under consideration with the accuracy of 10 % [8]:

$$\sigma_{fus} = \frac{1.074 \cdot 10^5 + 330\varepsilon - 0.0635\varepsilon^2}{\varepsilon} \times \times \exp\left(-\frac{44.4}{\sqrt{\varepsilon}}\right), \quad (8)$$

where the fusion cross section σ_{fus} is expressed in mbarn (10^{-27} cm^2) and the energy of the fast deuteron in the laboratory frame of reference is given in keV.

Table 1 contains the values $w_{fus}(\varepsilon)$ of the probability for a fast deuteron to take part in the fusion reaction in the course of its stopping in collisions with slow deuterons, in accordance with Eq. (7). Because the cross section of elastic scattering is large in comparison with the fusion cross section, this probability is small in the energy range under consideration, i.e., the Lawson criterion is not fulfilled in this case. Next, the probability $w_{fus}(\varepsilon)$ is approximated by the dependence

$$w_{fus}(\varepsilon) = C \exp\left(-\sqrt{\frac{\varepsilon_0}{\varepsilon}}\right), \quad (9)$$

where $C = 0.18$ and $\varepsilon_0 = 7.00$ MeV in the range $\varepsilon = 20$–200 keV.

It is important that the fusion probability $w_{fus}(\varepsilon)$ is independent of the target density because the stopping rate and the fusion rate have similar dependences on the target density. Nevertheless, we assume that the target thickness is sufficient for braking a fast deuteron. The braking is the result of elastic scattering on nuclei; therefore, the same dependence of the fusion probability on the initial deuteron energy ε applies for different deuterium-containing targets. Because the Coulomb logarithm is approximately the same for different targets, it follows from Eq. (6) that

$$w_{fus}(\varepsilon) \approx \frac{1}{Z^2},$$

where Z is the effective charge multiplicity of target nuclei. This quantity is given by

$$Z^2 = \frac{1}{n_D} \sum_i n_i Z_i^2, \quad (10)$$

where n_i is the number density of atoms of the ith component in the target molecule and Z_i is the charge multiplicity of the corresponding nucleus. In particular, we have $Z^2 = 1$ for the deuterium target, $Z^2 = 10$ for the CD_4 target, and $Z^2 = 33$ for the D_2O target.

Figure 1 contains the values of $w_{fus}(\varepsilon)$ in accordance with Eqs. (6), (8), and (10) when a fast deuteron is braked in different targets. In the case of a deuterium target, this result is in agreement with Eq. (9); the latter is better at high deuteron energies.

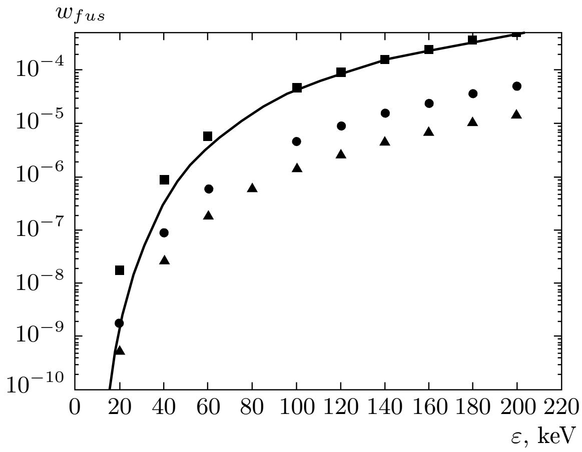

Fig. 1. The probability (Eq. (6)) of neutron generation for a fast deuteron braked in a deuterium-containing target as a function of the initial deuteron energy. Squares — D_2, circles — CD_4, triangles — D_2O, solid curve — approximation in Eq. (9)

The tail of the distribution function of fast deuterons can be approximated by the Maxwell distribution function

$$f(\varepsilon) = \frac{2}{\pi^{1/2} T^{3/2}} \varepsilon^{1/2} \exp\left(-\frac{\varepsilon}{T}\right), \quad (11)$$

where T is the temperature (in energy units). In this case, it is convenient to introduce the probability $w_{fus}(T)$ as

$$w_{fus}(T) = \int_0^\infty w_{fus}(\varepsilon) f(\varepsilon) d\varepsilon. \quad (12)$$

Table 2 contains the values of $w_{fus}(T)$ in the appropriate temperature range.

3. BRAKING OF DEUTERONS IN DEUTERIUM-CONTAINING MATTER

Along with the fusion reaction rate, the mean free path of a fast deuteron is of great importance. The mean free path λ of a fast deuteron with respect to its stopping follows from Eq. (4); it is given by

$$N_i \lambda = \frac{\varepsilon^2}{32\pi Z^2 e^4 \ln \Lambda}, \quad (13)$$

where ε is the initial deuteron energy and N_i is the number density of target deuterons. The mean free

Table 1. Data of the fusion reaction for a fast deuteron during its stopping in collisions with slow deuterons

ε, keV	$w_{fus}(\varepsilon)$	$N_i\lambda$, 10^{21} cm^{-2}	$N_i\lambda_{fus}$, 10^{21} cm^{-2}	λ_s, mm
20	$1.8\cdot10^{-8}$	0.20	0.035	0.045
40	$8.9\cdot10^{-7}$	0.82	0.18	0.18
60	$5.8\cdot10^{-6}$	1.8	0.48	0.40
80	$1.9\cdot10^{-5}$	3.3	0.94	0.72
100	$4.5\cdot10^{-5}$	5.1	1.6	1.1
120	$8.8\cdot10^{-5}$	7.4	2.4	1.6
140	$1.5\cdot10^{-4}$	10	3.4	2.2
160	$2.4\cdot10^{-4}$	13	4.7	2.8
180	$3.4\cdot10^{-4}$	17	6.1	3.6
200	$4.8\cdot10^{-4}$	20	7.8	4.5

path λ_{fus} that is responsible for the fusion reaction is less than λ, i.e., than the total mean free path in Eq. (13) with respect to the deuteron stopping; it is given by

$$N_i\lambda_{fus} = \int\limits_0^{\varepsilon_0} \frac{\varepsilon w_{fus}(\varepsilon)d\varepsilon}{\pi Z^2 e^4 w_{fus}(\varepsilon_0)\ln\Lambda}. \qquad (14)$$

In particular, assuming a strong dependence $w_{fus}(\varepsilon)$, we can simplify Eq. (14) to

$$\lambda_{fus} = \lambda\frac{2\Delta\varepsilon}{\varepsilon_0}. \qquad (15)$$

Table 1 contains the reduced values of the parameters λ and λ_{fus}. It can be seen that these values are comparable.

We now determine the parameters of a solid target, thin foils or solid clusters. We take the densities of deuterium-containing compounds in [9, 10]. Table 3 contain these parameters: ρ is the mass density of a solid, N is the number density of compound molecules, and N_D is the number density of deuterium atoms. The mean free path of deuterons λ_s for a deuterium target derived in accordance with these data is given in Table 1.

We can see a weak braking of deuterons in a deuterium-containing target. This is the result of the weak Coulomb scattering of fast deuterons on target nuclei. In addition, another mechanism of deuteron braking operates at the excitation of the electron subsystem of the target [11, 12]. This mechanism is absent at strong excitation of the target, in particular, at the fast ionization of the target by a cluster beam. In this case, the total ionization of target atoms requires small energy compared to that obtained in the Coulomb scattering. Thus, we assume a weak excitation for the initially nonexcited target.

Table 2. The probability $w_{fus}(T)$ in the case of the Maxwell distribution of fast deuterons braked in the indicated targets

T, keV	D_2	CD_4	D_2O
5	$2.5\cdot10^{-9}$	$2.5\cdot10^{-10}$	$7.6\cdot10^{-11}$
10	$1.3\cdot10^{-7}$	$1.3\cdot10^{-8}$	$3.9\cdot10^{-9}$
15	$9.4\cdot10^{-7}$	$9.4\cdot10^{-8}$	$2.9\cdot10^{-8}$
20	$3.3\cdot10^{-6}$	$3.3\cdot10^{-6}$	$1.0\cdot10^{-7}$
30	$1.6\cdot10^{-5}$	$1.6\cdot10^{-6}$	$4.8\cdot10^{-7}$
40	$4.2\cdot10^{-5}$	$4.2\cdot10^{-6}$	$1.3\cdot10^{-6}$
50	$8.4\cdot10^{-5}$	$8.4\cdot10^{-6}$	$2.5\cdot10^{-6}$
60	$1.4\cdot10^{-4}$	$1.4\cdot10^{-5}$	$4.3\cdot10^{-6}$

Table 3. Parameters of solid deuterium-containing compounds

Compound	D_2	CD_4	D_2O
ρ, g/cm^3	0.15	0.53	1.1
N, 10^{22} cm^{-3}	2.3	1.6	3.3
N_D, 10^{22} cm^{-3}	4.6	6.4	6.7

4. FUSION AT THE LASER EXCITATION OF A DEUTERIUM CLUSTER BEAM

In the experiments in [2–4, 13–15], neutrons are generated excitation of a deuterium cluster beam by a femtosecond focused laser beam. This gives a compact source of neutrons and also allows analyzing the processes of neutron production. The general concept of this process given in [16–19] is used. At the excitation of a cluster beam, clusters absorb laser radiation and obtain large enough internal energy. As a result, electrons of deuterium molecules are ionized, and electrons are kept during a certain time inside the cluster under the action of a self-consistent internal field. The electrons leaving the cluster create a high electric potential of the cluster, which leads to the Coulomb explosion of the cluster. Flying ions gain a high energy due to the electric cluster potential. This energy determines the possibility of neutron generation after decomposition of clusters when a uniform hot plasma is formed.

Production of fast deuterons in this process depends on both the laser radiation power and the cluster size. These parameters affect penetration of the laser signal inside the cluster and together with the pulse duration determine the energy obtained by one deuteron. We analyze the processes of neutron generation from this standpoint. On the basis of the above estimates, we find a typical ion energy in experiments. We know the number of deuterons in clusters in an excited cluster beam; the number of produced neutrons is also measured in experiments. The ratio of these values gives the probability w_{fus}. Because it depends strongly on the initial deuteron energy ε, we can determine the deuteron energy for a given experiment. Some results of this analysis are given in Table 4. The clusters consist of deuterium molecules D_2 or of molecules CD_4, J is the intensity of a laser pulse, E is the pulse energy , τ is the pulse duration, n is the number of produced neutrons per laser pulse, and ε is a typical deuteron energy that corresponds to Eq. (6) for the efficiency of the fusion reaction.

The main process at the neutron generation is the outer ionization of clusters. The Coulomb explosion of charged clusters results in a high kinetic energy of the deuterons that is used in the subsequent fusion reaction. The same process can also be realized at irradiation of deuterium solid targets by a laser pulse. According to experiments, the neutron yield is higher in this last case. At the irradiation of carbon–deuteron targets, more than 10^7 neutrons per laser pulse were measured [17, 23]. This is explained by the possibility of using long (picosecond) laser pulses for the irradiation.

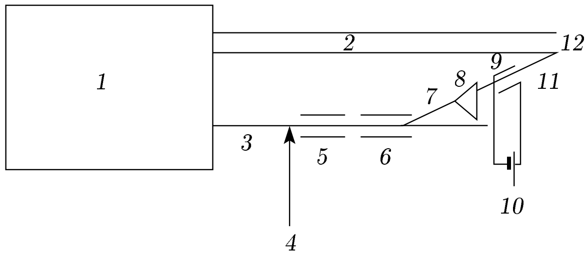

Fig. 2. The scheme of generation of neutrons based on a beam of deuterium clusters: *1* — container with gaseous deuterium for generation of cluster beams; *2* — wide beam of slow deuterium clusters; *3* — narrow beam of deuterium clusters; *4* — electron beam for ionization of deuterium clusters; *5* — collector of electrons; *6* — a weak electric field for deviation of charged clusters; *7* — beam of charged clusters; *8* — skimmer; *9* — a gap for acceleration of charged clusters; *10* — the source of a pulsed strong electric field; *11* — accelerated beam of charged clusters; *12* — the region of fusion reaction where accelerated clusters collide with slow clusters

Of course, the considered model of processes in cluster plasmas is very crude. In particular, the observed anisotropy of the angular distributions of produced neutrons can be explained by some collective phenomena at the acceleration of deuterons.

5. NEUTRON GENERATION IN COLLISIONS OF DEUTERIUM CLUSTER BEAMS

Among other methods of neutron generation, we separately consider neutron generation as a result of collision of two deuterium beams. Figure 2 demonstrates the scheme of neutron generation due to collisions between fast deuterium cluster beams. A cluster beam is here formed by the standard method of free jet expansion of gaseous deuterium. Thus, two cluster beams are produced, a narrow and a broad one, and the latter used as a target. The narrow cluster beam is intersected by a beam of electrons with the appropriate electron energies, which leads to ionization of some clusters. As a result, the cluster beam contains neutral clusters, charged clusters, and free electrons. Electrons are partly gathered by a collector; positive-charged clusters then acquire a transverse momentum after passing a region with an electric field. Hence, they move at some angle with respect to the initial cluster beam. These clusters are separated by a skimmer from the basic cluster beam. Then they are accelerated by a strong electric field. We note that the intensity of this

Table 4. Parameters of laser fusion for a target consisting of a cluster beam and for a laser wavelength about 0.8 μm

Target	E, J	J, W/cm^2	τ, fs	n	ε, keV	Reference
D_2	0.12	$2\cdot10^{16}$	35	$1\cdot10^4$	2.5	[2]
D_2	10	$2\cdot10^{20}$	100	$2\cdot10^6$	15	[20]
CD_4	0.8	$2\cdot10^{17}$	35	$7\cdot10^3$	2	[4]
CD_4	2.5	$4\cdot10^{19}$	100	$1\cdot10^5$	10	[21]
D_2O	0.6	$1.2\cdot10^{20}$	35	$6\cdot10^3$	25	[22]

secondary cluster beam is approximately 10^{-4} times the intensity of the basic cluster beam.

We estimate some parameters in this approach. The kinetic energy of the fast charged clusters is taken to be 60 keV per deuteron, which corresponds to the cluster speed $v_d = 2.4\cdot10^8$ cm/s. Slow clusters move with the speed of sound of approximately 10^5 cm/s. Guided by the modern sources of electric fields [24], we choose the electric field strength in the gap as $E = 10^6$ V/cm. The time of cluster acceleration is $t \approx 20$ ns, which is in agreement with parameters of pulse sources [24]. Of course, the power of the generated electric signals is relatively small.

This beam intersects a broad dense cluster beam, such that collisions of fast charged clusters lead partially to fusion reaction (1). Although the probability of the fusion reaction for a test fast deuteron in the process of its deceleration is small, a certain number of neutrons are nevertheless generated in each pulse. The neutron yield for this scheme is analyzed below.

In accordance with experiments [17], the average number of deuterium atoms in the cluster is $n = 3\cdot10^4$ and the average number density of deuterium atoms in the cluster beam is $3\cdot10^{19}$ cm^{-3}.

Each deuteron acquires the kinetic energy around 60 keV in the beam of positive-charged clusters. The high voltage $U = 3$ MV is divided between approximately 50 deuterons, i.e., each cluster contains 50 deuterium atoms (or 25 deuterium molecules). Such a small number of atoms may be attained by a small nozzle size and by preliminary deuterium expansion [25, 26].

We now determine the number density of the accelerated charged clusters inside the gap. This quantity must be chosen from the condition that the external electric field be able to separate charged clusters from free electrons. Using the Poisson equation for the number density of elementary charges inside the gap, we find

$$N_i = \frac{E}{2\pi e L},$$

where $E = 10^6$ V/cm is the electric field strength inside the gap. We obtain $N_i \approx 2\cdot10^{11}$ cm^{-3}, and the number density of the accelerated deuterons is $N_d \approx 1\cdot10^{13}$ cm^{-3}. We note that a decrease in the gap size leads to an increase in the limiting charge density but reserves the limiting number density of deuterons. Taking the separation $L = 1$ mm between the gap plates, we find the total number of accelerated deuterons $n \approx 10^{12}$ (their weight is of the order of 0.3 ng). Acceleration of these deuterons requires the energy 3 mJ; hence, the power of the electric pulse must be approximately 200 kW.

When fast deuterium clusters collide with slow clusters, molecules of fast clusters penetrate into slow clusters. Because scattering of colliding deuterons proceeds at small distances between them in comparison with distances between neighboring deuterons in the cluster, this scattering is determined by pair collisions. A fast deuteron is decelerated in elastic collisions with slow deuterons, and the cross section for fusion reaction (1) decreases. We determine the probability w_{fus} for a fast deuteron to take part in fusion reaction (1) in the process of its deceleration. According to [8], the cross section σ_{fus} depends sharply on the energy ε. The cross section for elastic scattering between fast and slow deuterons is determined by Eq. (2). In particular, using the data for fusion cross sections in Ref. [8], we use Eq. (4) to find $\varepsilon = 60$ keV for the cluster kinetic energy per deuteron (or $E = 30$ keV in the center-of-mass frame) and $w_{fus} = 1\cdot10^{-6}$ per fast deuteron. In this case,

$$\sigma_{fus}(\varepsilon) = 6.9\cdot10^{-27}\ \text{cm}^2$$

and

$$\frac{d\ln\sigma_{fus}}{d\varepsilon} = 2.1.$$

If the kinetic energy is $\varepsilon = 100$ keV, we similarly obtain

$$w_{fus} = 1 \cdot 10^{-5}, \quad \sigma_{fus}(\varepsilon) = 1.65 \cdot 10^{-26}\ \text{cm}^2,$$

$$\frac{d \ln \sigma_{fus}}{d\varepsilon} = 1.5.$$

Therefore, the Lawson criterion is not fulfilled in the framework of this scheme of neutron generation.

These values lead to a number of generated neutrons 10^6 at the fast deuteron energy $\varepsilon = 60$ keV. This is an overstated value because we assume that the time of cluster acceleration exceeds the time during which the electric field is switched on, whereas these values are comparable in practice. Next, the mean free path of fast deuterons in a dense cluster beam is about 5 cm if the typical total number density of deuterium molecules in the cluster beam is $3 \cdot 10^{19}$ cm^{-3}. We consider deceleration of fast deuterons as a result of their random collisions with slow deuterium molecules. A fast deuteron is braking on this length, and hence the probability that it takes part in a fusion reaction decreases significantly. But the mean free path of fast deuterons is less in practice because they are joined into clusters and collide with slow clusters. In particular, if the typical number of deuterons in the cluster is $n_d = 3 \cdot 10^4$, the mean free path of fast clusters with respect to their collisions with slow clusters is approximately 10^{-3} cm. Inclusion of deuterium molecules into clusters facilitates their collisions with other clusters.

The processes under consideration are analogous to the laser method of neutron generation at the irradiation of a beam of deuterium clusters by a femtosecond laser pulse. When the peak intensity of a laser pulse is $2 \cdot 10^{20}$ W/cm^2, and the wavelength is 800 nm, the pulse duration is 100 fs–1 ps, and the average cluster radius is 5 nm ($3 \cdot 10^4$ deuterons per cluster), we obtain about 10^6 neutrons per pulse at the average deuteron energy 10 keV. Neutrons are formed during 1.5 ns after the end of the laser pulse. The maximum yield is achieved at 0.7 ns after the laser pulse [15]. The time of radius doubling for an expanding cluster is 20 fs [14]; hence, fusion reactions occur in a uniform microplasma produced after the cluster explosion. This plasma expands into the surrounding region during a typical time of the order of 1 ns.

We note that the method of transformation of the kinetic energy of a cluster beam involved here is different from the method used for generation of X-rays in a collision of two cluster beams consisting of heavy atoms [27]. In the latter method, the kinetic energy of cluster beams is converted into the excitation energy of the electron component of colliding clusters; in the former, the energy of fast deuterons is lost in elastic collisions with atoms of another cluster. In both methods, atoms of one cluster colliding with another cluster penetrate into each other; the energy exchange occurs due to collisions of the individual deuterons.

6. CONCLUSION

Our analysis shows that the modern sources of high voltage allow generating neutrons in collisions of cluster beams accelerated by an external electric field pulse of a high voltage. This method is analogous to the laser method based on the irradiation of cluster beams by superintense femtosecond laser pulses. However, these methods use different experimental facilities and are therefore alternative each to other.

According to the character of the neutron generation, this method is similar to the acceleration of deuterium molecular ions; it uses this acceleration for the fusion reaction. The cluster method of neutron generation can be analyzed from this standpoint. First, because the kinetic energy is transferred to many deuterons owing to acceleration of one charge, there is an additional possibility of optimization depending on the accelerating voltage. Second, if the limiting parameters are determined by a charge or by a charge density of deuterons, using clusters allows increasing the neutron yield. Third, it is easier to create a high-intensity beam of charged molecular deuterium ions than that of charged clusters. All these considerations make the cluster scheme of neutron generation more attractive than the method of molecular ions.

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