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Hot laser fusion or low temperature nuclear reactions? Analysis and current prospects of the first experiments on laser fusion

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Abstract: The paper considers the features and quantitative characteristics of the first successful laser experiments on the formation of a thermonuclear plasma and registration of neutrons in nuclear fusion reactions under pulsed irradiation of a LiD crystal. Quantitative analysis shows that the production of neutrons recorded in these experiments is not associated with thermonuclear reactions in hot laser plasma. The most probable mechanism of neutron generation is associated with nuclear reactions at low energies and is due to the formation of coherent correlated states (CCS) of deuterons. In this experiment, such states can be formed in two different processes: due to the effect of a shock wave in the undisturbed part of the target lattice on the vibrational state of deuterium nuclei or when deuterium nuclei with an energy of about 500 eV move in the lattice. This part of the deuterium nuclei corresponds to the high-energy "tail" of the Maxwellian distribution of the total flux of particles entering from the laser plasma into the interplanar channel. In this second case, the process of the formation of the CCS is associated with the longitudinal periodicity of the interplanar crystal channel, which is equivalent to a nonstationary oscillator in the own coordinate system of moving particle. The expediency of repeating these experiments is shown, in which, in addition to neutrons, one should expect a more efficient generation of other nuclear fusion products due to low-energy reactions involving lithium isotopes from the target composition.

Keywords: laser and thermonuclear fusion, nuclear reactions at low energy, coherent correlated states, tunneling effect

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1. INTRODUCTION

The question of realizing of energy-efficient controlled nuclear fusion is undoubtedly one of the most actual and widely discussed problems. Special interest to this problem is due to the fact that the potential and effectiveness of such reactions does not need to be proved, since all life on Earth is due to the Sun, where such processes have been continuously going on for 5 billion years. Real study of this problem began in the mid-50s after the implementation of uncontrolled fusion in the form of a hydrogen bomb, when most of the scientists who had previously dealt with purely explosive topics (including such outstanding physicists as A.D. Sakharov, L.A. Artsimovich, I.E. Tamm, I.V. Kurchatov), quickly came to a consensus on the basic idea: the implementation of a controlled thermonuclear fusion based on high-temperature plasma with magnetic confinement in systems of the TOKAMAK type. The initially unrecognized exceptional complexity of the task of confining high-temperature plasma in such a system turned out to be a tough nut to crack. Despite huge financial investments, it did not allow for the next 60 years to create a successful and energy-efficient prototype of such a device. An alternative model of inertial confinement of short-lived dense hot plasma eliminated the problem of magnetic confinement and was directly associated (on a smaller scale) with uncontrolled fusion in a hydrogen bomb, but required corresponding high-speed efficient drivers. The successes of the synchronously developing laser physics were the impetus that led to the idea of laser inertial fusion. It is quite natural that those outstanding scientists (primarily N.G. Basov) who very successfully creating high-power pulsed lasers, quickly came up with the idea of using such lasers to implement inertial thermonuclear fusion. The idea of using powerful lasers to implement controlled thermo-nuclear synthesis was first

expressed in 1960 by A.D. Sakharov on the basis of a modernized explosive thermonuclear fusion scheme (a hollow mirror ellipsoid, in the foci of which there is a compressible fuel and a laser radiation source). A more realistic scheme for heating and compressing a target by laser radiation was proposed in 1961 by N.G. Basov and O.N. Krokhin.

2. ANALYSIS OF THE FIRST EXPERIMENTS ON LASER SYNTHESIS

The first experiments on the realization of nuclear fusion stimulated by laser action on a target were carried out in the late 1960s [1-3] according to the simplified scheme shown in Fig. 1 and does not imply target compression.

It was assumed that intense one-sided localized heating of a small part of the target surface using short ($\sim 10^{-11}$ s) single laser optical pulses with an energy of about 10 J, generated by a high-power neodymium laser with a wavelength of 1.06 μm , during the action of each pulse on the LiD surface target would allow to realize such a short-term hot plasma, within which thermonuclear fusion will be possible until the moment of expansion. To increase the radiation intensity, a long-focus lens was additionally used, which made it

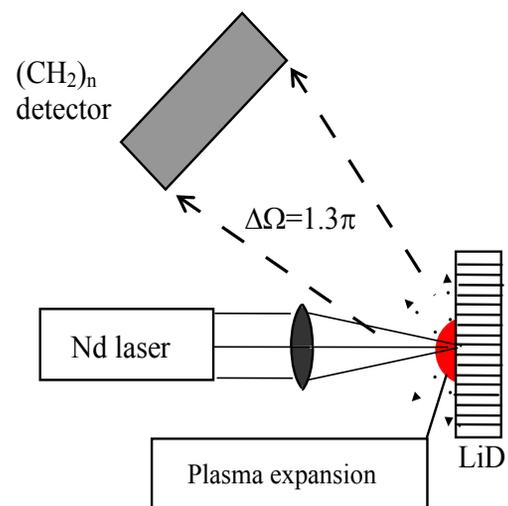


Fig. 1. General scheme of experiments on laser synthesis of neutrons in a LiD target.

possible to achieve a record intensity of $J \approx 10^{16}$ W/cm². It should be noted that even 50 years after these experiments, such an intensity is quite adequate for such studies, and even today these parameters significantly exceed only the pulses generated by modern picosecond or femtosecond lasers.

The authors of the experiments expected that in the hot plasma formed near the target surface, synthesis based on one of the d - d synthesis channels would be possible

$$d + d = He^3 + n + 3.27 \text{ MeV}, \quad (1)$$

implementing due to collision of deuterons into the hot plasma.

To confirm the implementation of such a synthesis, a scintillation detector based on a polystyrene (CH₂)_n crystal was used. According to the authors' estimates, the neutron detection efficiency, taking into account the geometric parameters of the detector, the solid angle of registration $\Delta\Omega = 1.3\pi$ and the probability of the formation of optical quanta during the interaction of neutrons with hydrogen nuclei, corresponded to $\eta \approx 10\%$.

From the results of experiments [1,2] it follows that under such a pulsed action, on average $N_{neutron} \approx 1$ neutron was recorded for each laser pulse, which corresponded to generation

$$N_{neutron}^0 \approx N_{neutron} / \eta \approx 10 \text{ neutrons/pulse} \quad (2)$$

These data were interpreted by authors as the first demonstration of the inertial laser thermonuclear (hot) synthesis. It should be noted that in [1-3] a very detailed analysis of the process of formation of hot plasma using specific laser pulses was carried out, but the quantitative features of nuclear fusion were almost not considered and the results of experiments were not compared with the calculated parameters of the expected hot fusion.

Such an analysis can be easily carried out on the basis of a technique that is now widely used both for the analysis of similar problems in laboratory and industrial nuclear fusion, as well

as in the analysis of astrophysical processes in stars.

According to the authors of [1-3], during the action of each of the laser pulses on the LiD target, plasma with the following parameters was formed:

- deuterium ion concentration - $n_d \approx 10^{21}$ cm⁻³;
- average thickness of the plasma region near the laser focus - $x_0 \approx 10^{-2}$ cm;
- the temperature of the ion component of the plasma - $kT_{max} \approx 120$ eV corresponded to the close-to-spherical geometry of its expansion (see. [3], Fig. 10);
- the lifetime of a plasma with such a temperature - $\tau \approx 5 \cdot 10^{-10}$ s;
- rms velocity of deuterium ions in plasma at maximum temperature - $\langle v \rangle \approx \sqrt{3kT/M} \approx 10^7$ cm/s.

If we assume that the area of transverse expansion of the plasma (taking into account the initial cross section of the focused laser pulse $S_0 = \pi R_0^2 \approx 3 \cdot 10^{-4}$ cm²) during its existence was equal $S_\tau \approx \pi(\langle v \rangle \tau + R_0)^2 \approx 6 \cdot 10^{-4}$ cm², then in the volume of plasma there were $N_d = n_0 S_\tau x_0 \approx 6 \cdot 10^{15}$ deuterium nuclei.

Based on these data, taking into account the cross section of the reaction $\sigma(v)$ and the speed of the particles participating in it, it is possible to calculate the total number ($d-d$) of reactions and, accordingly, the total number of generated neutrons,

$$N_{neutron}^0 \approx V n_0^2 \langle \sigma(v)v \rangle \tau / 2, \quad (3)$$

in the volume of the laser plasma during its existence τ .

The standard expression for the reaction rate $\sigma(v)v$ averaged over the Maxwellian distribution of ions in the plasma is determined by the well-known formula (eg, [4], Chapter 2)

$$\langle \sigma(v)v \rangle_{dd} \approx 1.3 \cdot 10^{-14} \frac{1}{(kT)^{2/3}} \exp\left(-\frac{18.8}{(kT)^{1/3}}\right) [\text{cm}^3/\text{s}] \quad (4)$$

Here kT corresponds to the plasma temperature in units of keV.

Substituting the above parameters, we can find $\langle\sigma(v)v\rangle_{dd} \approx 5 \cdot 10^{-30} \text{ cm}^3/\text{s}$.

When this quantity is taken into account, from (3) it follows an estimate of the average number of neutrons generated in experiments [1,2] when a single laser pulse is exposed to a LiD target

$$N_{neutron}^0 \approx 0.007 \text{ neutrons/pulse.} \quad (5)$$

This value is 1500 times less than the estimate (2), which was made by the authors of the experiments on the basis of the neutron registration process under experimental conditions [1,2].

It is obvious from these estimates that the considered thermonuclear mechanism can provide only 0.07% of the total number of neutrons generated in the experiments performed.

We have no doubt about the very high qualifications of the authors of works [1-3] and the correctness of their measurements, but the question immediately arises about the mechanism and substantiation of those processes that led to the generation of neutrons under the one-sided action of single laser pulses on the LiD target.

3. AN ALTERNATIVE MECHANISM FOR THE GENERATION OF NEUTRONS AND OTHER PARTICLES UNDER THE ACTION OF A LASER PULSE ON A LiD TARGET

The subsequent analysis shows that the neutrons recorded in the experiments under consideration were generated in the process of low-energy nuclear reactions (LENR), which were stimulated by effects that are not directly related to an increase in the temperature of deuterium nuclei under the action of laser pulses on the target surface and are realized even at relatively low energy and temperature.

Two basic mechanisms that are based on the same physical process and lead to efficient nuclear fusion can be noted.

3.1. FEATURES OF NUCLEAR REACTIONS AT LOW ENERGY IN NONSTATIONARY MICROCRACKS STIMULATED BY THE ACTION OF A LASER PULSE ON THE TARGET

It is well known that when a laser pulse acts on a target, an ablation process always takes place due to intense pulsed evaporation of fast ions from that part of the target surface on which the laser pulse acts. This evaporation is accompanied by the transfer of momentum to the target, which leads to the formation of an intense shock wave moving deeper into the target perpendicular to its surface. Such a mechanism for generating shock waves is well known (eg, [5-9]).

The shock pressure on the remaining (non-evaporated) part of the target surface with this ablation mechanism is $P \approx 4 \cdot 10^6 \text{ atm}$ at a laser pulse intensity $J = 10^{13} \text{ W/cm}^2$ [5]. With an increase in the laser pulse intensity, the pressure sharply increases $P \sim J^{7/9}$ [8,9], reaching gigantic values $P \approx 10^8 \dots 10^9 \text{ atm}$ at an intensity $J \approx 10^{16} \text{ W/cm}^2$ corresponding to this experiment.

The speed of the front of the shock wave with the above parameters of the laser pulse can reach or exceed 4...8 km/s. When this shock wave moves inside any material bodies, a very sharp narrowing of its leading front occurs to a size limited by several free path lengths of the accelerated ions. In the case of a solid target, the minimum value of the leading edge corresponds to several nm. This "steepening" of the shock front is due to the fact that the more intense (increasing) part of the shock front, due to the nonlinearity of the interaction process, moves faster than the less intense front part of the front and "catches up" with it.

The passage of this shock wave through a target containing deuterium and lithium leads to a very fast ($\sim 10^{-11} \dots 10^{-13} \text{ s}$) shock compression, and then rapid expansion and subsequent slower relaxation of the local environment of

each of the deuterium and lithium atoms in the target. From the point of view of crystal lattice dynamics, these processes correspond to very fast pulsed reversible modulation of parameters and vibration frequency of a nonstationary harmonic oscillator characterizing the vibrational state of each of the deuterium nuclei in the lattice (including optical phonon modes at frequencies of 10...15 THz).

Such very fast process of nonstationary modulation leads to phase synchronization (otherwise, constructive interference) of optical phonon modes of the same particle and to the formation of a coherent correlated state (CCS) of these particles (nuclei). It leads to the generation of giant fluctuations of the momentum and energy of the corresponding nuclei accompanying these states [10-23]. Obviously, this mechanism of pulsed modulation of the parameters of the local oscillator is much more effective in the region adjacent to the target surface, near which the laser plasma is formed. In this region, even before the arrival of the shock wave, numerous nanocracks arise, which are formed due to the entry of fast ions, escaping from the volume of the near-surface plasma. This process is similar to the cracking procedure for metal hydrides of the TiD or TiH type upon their rapid saturation with hydrogen isotopes. The relatively large width of these nanocracks filled with deuterium sharply (several times) increases the amplitude of the possible modulation of the frequency of deuteron oscillations upon the subsequent action of a shock wave on this nanocrack. Another important result of the action of the shock wave is the accelerated "opening" of those nanocracks that had not yet formed, but were in a very stressed state due to the internal pressure of deuterons trapped in the interstice of the target lattice. This process is possible anywhere in the target.

It was shown in [10-17] that at such a very fast pulse modulation of the parameters of a nonstationary oscillator, the amplitude of

particle momentum fluctuations increases sharply, as a result of which fluctuations of the kinetic energy of a particle (in particular of a proton) can reach $\delta E_{\text{corr}} \geq 10...30$ keV even in the case of a crystal lattice at room temperature. An important fact is that during the generation of such gigantic fluctuations of momentum and energy, the average kinetic energy of these nuclei can remain invariably small and differ little from the thermal energy of the condensed target!

Another very important circumstance is the very long (compared to the case of uncorrelated states) lifetime of these giant fluctuations δt_{corr} , which is many orders of magnitude longer than the duration of possible uncorrelated fluctuations δt_{uncorr} , if it is estimated on the basis of the "usual" Heisenberg uncertainty relation $\delta t_{\text{uncorr}} \approx \hbar/2\delta E$.

The possibility of the existence of such coherent correlated states was described in the most general form (for different pairs of arbitrary dynamical variables A and B) in 1930 independently by Schrödinger and Robertson [18,19] on the basis of the general rules of quantum mechanics. In the general case, these relations are characterized by generalized uncertainty relations for the variances of these variables

$$\sigma_A \sigma_B \equiv (\delta A)^2 (\delta B)^2 \geq \frac{|\langle [\hat{A}\hat{B}] \rangle|^2}{4(1-r_{AB}^2)}, \quad \sigma_C \equiv \langle (\hat{C} - \langle C \rangle)^2 \rangle, \quad (6)$$

$$r_{AB} = \frac{\sigma_{AB}}{\sqrt{\sigma_A \sigma_B}}, \quad \sigma_{AB} = \frac{\langle \hat{A}\hat{B} + \hat{B}\hat{A} \rangle}{2} - \langle A \rangle \langle B \rangle, \quad |r_{AB}| \leq 1.$$

In particular, for pairs of variables "coordinate-momentum" or "energy-time" these states are characterized by the Schrödinger-Robertson relations, which are fundamentally different from the Heisenberg uncertainty relations

$$\delta p \delta x \geq \hbar / 2 \sqrt{1-r_{px}^2} \equiv \hbar G_{px} / 2, \quad (7)$$

$$\delta E \delta t \geq \hbar / 2 \sqrt{1-r_{Et}^2} \equiv \hbar G_{Et} / 2,$$

where $0 \leq |r| < 1$ and $1 \leq G < \infty$ are, respectively, the correlation coefficient and the

correlation efficiency coefficient for specific variables. These coefficients characterize the degree of inphase and mutual correlation of different eigenstates of a particle in a superposition quantum state (in particular, inphase of optical phonon modes of a deuteron in the space between neighboring lithium atoms in the lattice). It was shown in [20] that the coefficients r_{px} , r_{Ei} and G_{px} , G_{Ei} for each specific state are very close to each other.

For uncorrelated states $r = 0$ and $G = 1$, and for maximally correlated $|r| \rightarrow 1$ and $G \gg 1$. The characteristics of these states and the possibility of their application have been studied in many works (in particular, in articles [11-17,20-22]).

Particles in a coherent correlated state can "use" a large fluctuation of virtual kinetic energy $\delta E = (\delta p)^2/2M$ to pass through a potential barrier and then stimulate nuclear or chemical reactions if these processes correspond to exoenergetic reactions.

Such processes have been implemented many times in successful experiments on low-temperature nuclear fusion. Some of these experiments are described in [11-13,23].

The same mechanism, realized by the pulse modulation of the parameters of local equivalent harmonic oscillators when exposed to a shock wave, successfully substantiates the results of experiments on the generation of alpha particles under the action of low-amplitude high-frequency temperature waves, generated during cavitation of water jets, on the TiD targets [24-26]. The general scheme of these experiments and the corresponding results on the registration of generated alpha particles are presented in **Fig. 2**.

These experiments, if we consider them as a kind of realization of systems with shock action, are in some way similar to experiments with pulsed laser action. The mechanism of such an effect in such a system is associated

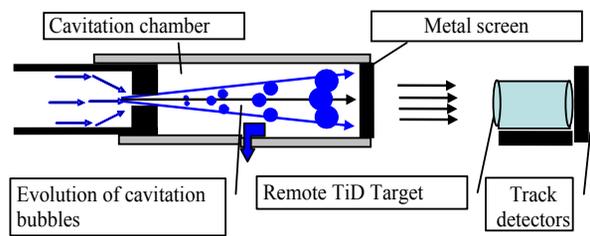


Fig. 2. Above is a diagram of experiments on the excitation of continuous temperature waves and the implementation of nuclear fusion using them. Below is a fragment of a track detector with tracks of alpha particles generated when such temperature waves act to a distant TiD target.

with the dynamics of the development of rapid cavitation of microbubbles in the volume of a water jet expanding after compression. The interaction of the jet in the state of cavitation with the metal wall of the chamber leads to the excitation of primary shock waves in the volume of this wall. Internal reflection of these waves from the outer wall leads to periodic excitation of surface atoms and, as a result, to the subsequent generation of both periodic pulses of soft (~ 1.5 keV) X-ray radiation and pulsed heating of the adjacent air. These processes are considered in details in [24-26].

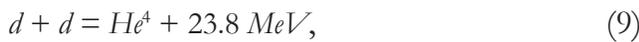
If the duration of these heat pulses is less than the thermal relaxation time τ in air, then at such a pulsed heating continuous temperature waves will be generated and propagated in air. Their frequency corresponds to the expression

$$\omega_n = \pi(n + 1/2)/\tau, n = 0,1,2... \quad (8)$$

The minimum frequency of such a wave at normal pressure and room temperature is $\omega_{min} \approx 75$ MHz.

The substantiation of the possibility of the existence of these waves and the results of their detailed theoretical and experimental study are considered in our works [24-26].

Such waves can propagate without significant attenuation over a long distance (up to many meters from the place of excitation). When these waves interact with a distant TiD target, secondary shock waves are excited in this target, which cause nuclear reactions with the participation of deuterons. Fig. 2 shows a view of the track detector, which was located near the rear wall of the TiD target obtained with preliminary enrichment (~150%) of the titanium sample with deuterium. The axial symmetry of the directions of motion of the registered alpha particles on this detector corresponded to the cylindrical shape of the TiD target. According to our estimates, the third possible channel of the d-d reaction was realized in these experiments



the probability of which for "standard" hot fusion is very small. In contrast, this channel is more likely to be implemented in the same systems based on LENR processes.

A more detailed description of these experiments is given in [15,24-26].

3.2. THE MECHANISM OF NUCLEAR FUSION AT LOW ENERGY, WHICH IS CONNECTED WITH THE MOVEMENT OF IONS IN THE CRYSTAL LATTICE OF THE TARGET

Another mechanism for the realization of reaction (1) is associated with an alternative method for the formation of CCS taking into account the interaction of moving ions with lattice atoms. It is due to the fact that in experiments [1,2] a great number of fast deuterium ions, which are formed during the formation of a laser plasma, move deep into

the unbroken crystal lattice of LiD in the channeling mode. It was shown in [16,17] that during a similar motion of relatively slow protons in the periodic field of the lattice of a lithium crystal, a similar CCS of a moving particle with a correlation coefficient $1 - |r| \leq 10^{-8}$ are formed very quickly (in an interval equal to 3 ... 4 lattice periods). It corresponds to the correlation efficiency coefficient $G \geq 10^4$ and to the increase of the energy of fluctuations in the transverse (with respect to longitudinal motion) direction to the value

$$\begin{aligned} \delta E &\approx (\delta p)^2 / 2M \geq G^2 \hbar^2 / 8M(\delta x)^2 \approx \\ &\approx G^2 \hbar^2 / 2Ma_x^2 \geq 40 keV, \end{aligned} \quad (10)$$

which is many orders of magnitude higher than the energy of longitudinal translational motion.

Here M is the proton mass, $a_x \approx 2\delta x \approx 2\text{\AA}$ is the interplanar distance in the lattice.

This mechanism of self-similar formation of CCS is fulfilled for those ions that move in the periodic field of the lattice with velocities close to the value $v_{opt} \approx 2a_z \langle \omega \rangle$, which provides synchronization of the eigenstates of the transverse quantized motion of the particle in the channel [16]. Here $\langle \omega \rangle$ is the average frequency of ion oscillations between planes during channeling in the averaged potential of the channel walls.

It was shown in [16] that a very large value of the coefficient G corresponds to particles with velocities in the range of approximately 10% of the optimal velocity v_{opt} for a given crystallographic direction. There are a lot of such particles with energies of several hundred eV on the "tail" of the Maxwellian distribution of laser plasma ions in experiments [1,2].

The spatial dynamics of the formation of CCS and the dependency of the correlation efficiency coefficient on the particle velocity in the lithium crystal lattice [16] is shown in **Fig. 3.**

The same dynamic mechanism of the CCS formation during the motion of an ion in a

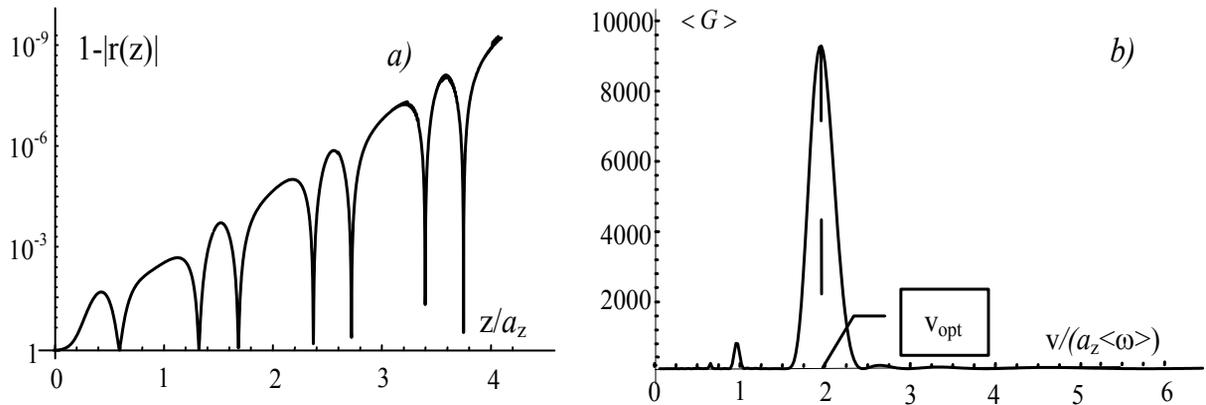


Fig. 3. a) spatial dynamics of the process of formation of a coherent correlated state during the motion of protons with an optimal energy of 450 ... 500 eV in a lithium crystal in the mode of in-plane channeling in the direction of the oz (a_z is the longitudinal lattice period of lithium); b) the dependence of the averaged correlation efficiency coefficient on the proton velocity at the end of the third lithium lattice period [16].

periodic field of a lattice or in the field of a cluster of several atoms explains well the results of numerous experiments carried out in several US laboratories (Louisiana Accelerator Center (Lafayette), Physical Dept. of North Texas Univ (Deuton) and NASA MFES Center in Huntsville). In these experiments a beam of accelerated protons with tunable energy $E \leq 500$ eV and two types of targets: a solid-state target in the form of a thin foil (~ 1 mm) of lithium and a target in the form of saturated vapors of the same lithium were used, as a result leading to efficient nuclear fusion (for details see [16,17]).

4. CONCLUSION

Both considered above mechanisms fully correspond to the definition of "nuclear reactions at low energy" or LENR, since they do not require heating or real (not virtual due to fluctuations) acceleration of particles to a typical thermonuclear energy of 10-15 keV and do not require the implementation of other conditions of hot thermonuclear fusion. It is very important that these types of reactions well substantiate the complete prohibition [14,20] on the realization of those channels of nuclear reactions that, after the fusion of the initial

particles, lead to the formation of radioactive compound nuclei. Such an extremely important result is differs greatly from typical reactions at high energies and, most importantly, is observed in all successful experiments at low energies without exception. A brief substantiation of such a feature of LENR reactions using the energy of giant fluctuations δE formed during the formation of coherent correlated states is due to the fact that a sufficiently long, but finite time of existence of these fluctuations δt_{corr} makes it possible to realize only those reaction channels in which a rapid return of the fluctuation energy δE , which was used to increase the transparency of the potential barrier, is realized. It is quite obvious that in any radioactive daughter nucleus such a return of energy occurs over a long time, which is many orders of magnitude greater than the value δt_{corr} and so such reactions are absolutely forbidden! In contrast, in reactions with really accelerated particles (including in systems of high-temperature nuclear fusion), there is no such a critical requirement, and in most reactions channels with the formation of both stable and radioactive nuclei are realized. These extremely important for practical applications

features of reactions with the use of CCS are considered in details in [20,23].

In addition to this, it should be noted that the analysis of experiments [1, 2] with the use of the CCS ideology also makes it possible to explain the relatively weak ($N_{neutron}^0 \approx 10$ neutron/pulse) efficiency of neutron generation, which was observed in these experiments. This is due to the fact that the neutron channel (dd) of the reaction $d + d = He^3 + n$, if we associate it with the formation of such CCS, turns out to be many orders of magnitude less probable [11,13] than the alternative and faster "proton" channel

$$d + d = T + p + 4.03 \text{ MeV.} \quad (11)$$

This is due to both the specificity (duration) of reactions stimulated by virtual energy fluctuations and the possible realization of the Oppenheimer-Phillips effect [27], which is connected with the mutual spatial reorientation of deuterons before their interaction, that leads to the capture reaction (4) without the formation of a compound nucleus He^A .

It is also important to point out that if a LiD target is used in the analyzed earlier laser experiments, other reactions with the participation of lithium isotopes, in which alpha particles and protons are formed, are also possible.

$$\begin{aligned} Li^6 + d &= Be^8 \rightarrow 2He^4 + 22.37 \text{ MeV,} \\ Li^6 + d &= Li^7 + p + 5.03 \text{ MeV.} \end{aligned} \quad (12)$$

Unfortunately, the authors of the first laser experiments [1,2] did not carry out control measurements of other potentially possible daughter products of these reactions, and these features remained unexplored and unnoticed.

Based on this analysis, it can be concluded that the most probable mechanism of neutron generation in the first laser experiments was associated not with the implementation of thermonuclear fusion, but with the implementation of nuclear reactions at low

energy due to the formation of coherent correlated states in the target volume under the action of a shock wave or during the motion of the formed ions in the undisturbed part of the target lattice [28].

The fact that such an analysis was not done 50 years ago is quite reasonable for a number of reasons. First of all, at that time some important circumstances, which relate to the peculiarities of nuclear reactions at high and low energies, were not understood and taken into account. Until recently, it was considered a priori that the region of low energies is completely unpromising from the point of view of nuclear energy based on charged particles. On the other hand, it is logically difficult to understand and accept the fact of completely ignoring of the influence of the effects of coherence and correlation on nuclear interaction, although the basic ideas of such effects were described back in 1930 in the works of Schrödinger and Robertson. In particular, as a completely inexplicable fact, it can be pointed out that none of the classical textbooks on quantum mechanics, on which all generations of physicists of the world were brought up in the 20th century, does not mention a word about such processes. In particular, nothing is written about the full ratio of the Schrödinger-Robertson uncertainties (6)-(7), from which, as a special case of an uncorrelated state, the famous Heisenberg uncertainty relation is obtained, which is well known and is used by everyone.

It should also be noted that the results obtained substantiate the possibility of alternative reactions in laser simulation of thermonuclear fusion. They show the advisability of a more detailed study and repetition of this and similar experiments in order to search for other possible nuclear fusion products using the same technique [1,2] at the action of unidirectional single or repetitive laser pulses. It is very important that such studies can be carried out in small laboratories and they do not require very complex, unique and expensive

equipment, which currently exists only in some world centers dealing with the solution of global problems of inertial thermonuclear fusion with mandatory all-round target compression by the time synchronized exposure to laser pulses generated by dozens of super-powerful lasers. Successful experiments on the implementation of nuclear fusion [24–26], carried out using temperature waves generated in a simple and extremely inexpensive cavitation setup based on a water jet, confirm the effectiveness of such studies.

Another conclusion concerns the need for a certain reevaluation of the role and efficiency of nuclear reactions at low energy in order to solve modern problems of nuclear technologies [29–31]. Obviously, in order to solve successfully such problems, it is necessary to take into account not only the specific interaction between a pair of particles under consideration, as is the case in high-energy nuclear physics, but also to fully analyze the influence of the environment on the efficiency of these processes. The world turned out to be more complex and a simplified analysis based on the separated from the environment pair interaction works well at high energy, but turns out to be quite far from reality at low energy.

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