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Research Article

Using the Method of Coherent Correlated States for Production of Nuclear Interaction of Slow Particles with Crystals and Molecules

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Abstract

In this paper, the possibility and characteristics of effective nuclear fusion based on the interaction of low energy proton beams with the nuclei on a crystal surface or gas of free molecules are discussed. It is shown that this effect can be explained by the process of formation of coherent correlated states, which take place during the interaction of moving protons with lithium molecules.
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1. Introduction

Traditionally, it has been believed that LENR ("Low Energy Nuclear Reactions") can occur only in condensed medium, such as a crystal or liquid, and can be produced only with a special form of the static local (interatomic) environment of interacting particles. This is reflected, in particular, in the "official" term for this area of nuclear physics: "Condensed Matter Nuclear Science". In our opinion the more correct and more universal term is LENR.

It is a very important fact that LENR effects not only take place in "traditional" crystals and solids, but also in low-temperature plasmas and in other media, which has no relation to condensed matter. One of the very interesting variants of such interaction is described in [1]. It is a low-energy variant of accelerator fusion, where nuclear fusion is induced by the proton beam with the energy no higher than several hundred electron volts, which is much lower than the energies of 30–100 keV, typical of the standard accelerator fusion. In these experiments the reaction of fusion

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$$Li^7 + p = 2He^4 + 17.3\ \text{MeV} \tag{1}$$

was observed with a count rate $J \approx 157$ pulse/s of fast alpha particles He^4 with an energy of about 8.6 MeV in the case of a lithium target (made of natural lithium) and the beam of protons with energy 448 eV (current $i_{\rm p} \approx 50\,\mu A$). This result cannot be explained within standard models of a nuclear reaction involving accelerated particles because at such energy the coefficient of barrier transparency and cross-section of reaction are very small ($D(E) \approx 10^{-50}$ and $\sigma(E) \approx 10^{-74}\text{cm}^2$).

If we consider that mean free path of protons with such low energy in the lithium crystal even in the planar channeling regime, it is shorter than $\langle L\rangle \approx 10{-}20$ nm. In such case, the differential $\mathrm{d}W_{\rm f}/\mathrm{d}z$ and total $W_{\rm f}$ probabilities of the fusion reaction per proton, as well as the total intensity of the reactions J for the beam with the current $i_{\rm p} \approx 50\,\mu A$, are also very small:

$$\mathrm{d}W_{\rm f}/\mathrm{d}z = \sigma\langle n_{\rm Li}\rangle \approx 3\times 10^{-50}\text{cm}^{-1}, \quad W_{\rm f} \approx \langle L\rangle\sigma\langle n_{\rm Li}\rangle \approx 10^{-56}, \quad J \approx i_{\rm p}W_{\rm f} \approx 10^{-41}\ \text{s}^{-1}. \tag{2}$$

These values are incommensurably insignificant in comparison with the results of the experiments.

In the same work [1] authors performed another variant of this experiment, when a proton beam with the energy varied from 50 eV to 5 keV and the current $i_{\rm p} \approx 100\,\mu A$ passes through lithium vapor. This experiment has no relation to the condensed matter.

The results of this experiment are very close to the results of experiments with lithium foil and are shown in Fig. 1. It can be seen that the nuclear interaction of moving protons with lithium vapor is characterized by a sharp peak with proton energy in a narrow range near 500 eV, where the maximum count rate of alpha particles reached $J \approx 4\times 10^4\ \text{s}^{-1}$. A typical spectrum of alpha particles in these experiments is presented in Fig. 2.

The most amazing feature of this spectrum is the complete absence of alpha particles with the energies of 1.7 and 2.3 MeV, which correspond to a fusion reaction

$$Li^6 + p = He^3 + He^4 + 4\ \text{MeV} \tag{3}$$

with the participation of Li^6 isotope! On the other hand, the "standard" calculation showed that the probabilities of both reactions ((1) and (3)) at a given energy should be approximately the same, which completely contradicts the experimental data.

We assume (and this will be proved below) that all features of the course of the reaction of accelerating fusion at such low energy are fully justified, and can be explained by the use of the method of coherent correlated states (CCS), which are automatically formed in the systems under consideration, both with lithium foil and lithium vapor.

2. Features of Formation of Coherent Correlated States of the Particles During its Passage Through the Crystal and Molecules of Gas

The method of CCS well explains the above-mentioned features and anomalies of nuclear reactions with the participation of low energy protons and lithium isotopes. This method provides a high probability of LENR and can be applied with the same efficiency to different experiments (including processes in solids, liquids, gas, plasma, at action of non-stationary magnetic fields, in geological and biological systems etc). It should be noted that the CCS method makes it possible to explain different LENR paradoxes on the basis of standard quantum mechanics and modern nuclear physics without involving fantastic heuristic models.

The physical basis of this method is related to the Schrödinger–Robertson uncertainty relations [2,3]

$$\delta p \delta q \geq \hbar/2\sqrt{1-r_{pq}^2} \equiv G_{pq}\hbar/2, \quad \delta E\,\delta t \geq \hbar/2\sqrt{1-r_{Et}^2} \equiv G_{Et}\hbar/2, \tag{4}$$

where $|r| \leq 1$ is a *correlation coefficient* and $G = 1/\sqrt{1-r^2}$ is a *coefficient of correlation efficiency* [6–10]. In works [4–19], it was shown that the mechanism of the formation of CCS with the sharp increase of up to $G \geq 10^3 - 10^4$ can be produced when the particle is localized in the field of a nonstationary harmonic oscillator and for different regimes of modulation of parameters of harmonic oscillator.

In this case if the particle is localized in a potential well with a width L, for which $\delta q \approx L/2$, then the kinetic energy fluctuations

$$\delta T^{(\min)} = (\delta p)^2/2m = G_{pq}^2\hbar^2/2mL^2 \tag{5}$$

are very large.

The methods for CCS calculations in different systems have been considered in detail in [4–19]. The simplest and the most adequate method involves analyzing the state of the considered particle in nonstationary parabolic field. In this case, the correlation coefficient can be calculated on the basis of the solution of equations

$$\begin{array}{l} \frac{d^2\varepsilon}{dt^2} + \omega^2(t)\varepsilon = 0, \quad \varepsilon(0) = 1, \qquad \left.\frac{d\varepsilon}{dt}\right|_0 = i, \quad \omega(0) = 1, \\ r = \mathrm{Re}\left\{\varepsilon^* \frac{d\varepsilon}{dt}\right\} / \left|\varepsilon^* \frac{d\varepsilon}{dt}\right|, \quad r^2 = 1 - 1/\left|\varepsilon^* \frac{d\varepsilon}{dt}\right|^2, \quad G = 1/\sqrt{1-r^2} \end{array} \tag{6}$$

Here, $\omega(t)$ is the dimensionless frequency in units of the characteristic frequency ω_0 and t is the dimensionless time in units of ω_0^{-1}. In particular, in works [9–12] it was shown that the maximum rate of G increase in the case of harmonic modulation $\omega(t) = 1 + g\,\cos\,\Omega t,\ |g| \ll 1$ (in dimensional form $\omega(t) = \omega_0(1 + g\,\cos\,\Omega t)$) corresponds to the condition, when the normalized oscillator modulation frequency Ω is two times greater than the average frequency ω_0 of the oscillator (see Fig. 3).

This mechanism and the results of analysis can be successfully used for proton moving with the velocity ν through a channel formed by a sequence of periodically arranged N pairs of atoms (fragment of the crystal lattice with longitu-

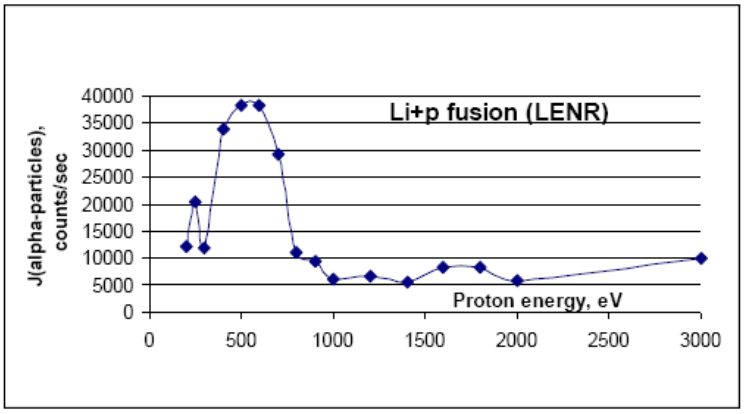

Figure 1. Intensity of the generation and detection of fast alpha particles versus the energy of protons passing through lithium.

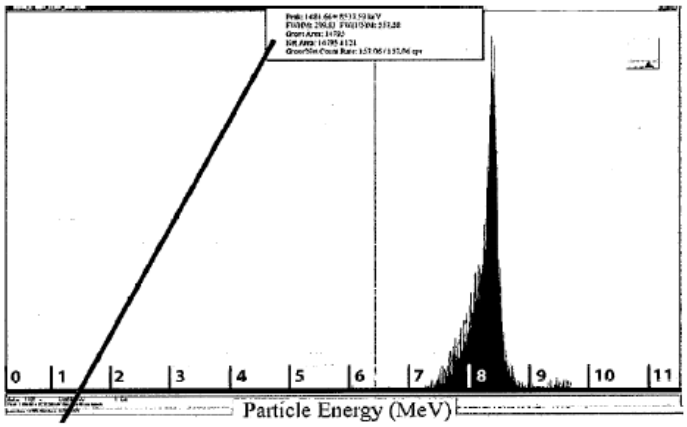

Figure 2. Experimental spectrum of detected alpha particles generated during Li+p fusion with participation of 500 eV protons passing through vapor of natural lithium.

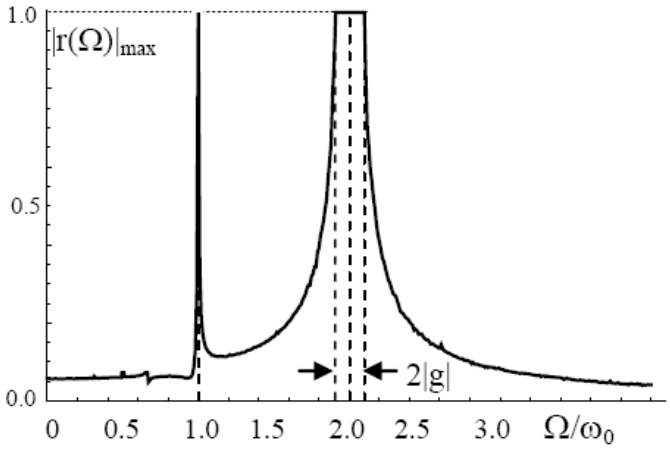

Figure 3. Resonance structure in the dependence of the maximum correlation coefficient on the modulation frequency $\omega(t) = \omega_0(1 + g\ \cos\ \Omega t)$ of the parameters of nonstationary potential well $V(x, t) = m_p x^2 \omega^2(t)/2$.

dinal a_z and transverse a_x lattice periods), which are located at the points $z_n = (n - 1/2)a_z,\ n = 1, 2, ...$ (see Fig. 4, *top*) and pairwise oriented perpendicularly to the direction of moon of the particle.

By analogy with the physics of channeling of positively charged particles, the electric field inside this channel can be approximately described by a parabolic potential (in the transverse direction). In contrast to the analysis of "traditional" channeling, which is valid only for sufficiently fast particles and involves the longitudinally averaged atomic potential of crystal axes and planes as the basic model, this analysis involves the real (not averaged) periodic potential $V(x, z) = V(x, z \pm a_z)$ with the period a_z in the direction of motion of the particle. In this model the character of proton motion in the periodic crystal field $V(x, z)$ corresponds to the inhomogeneous (along the longitudinal coordinate z)

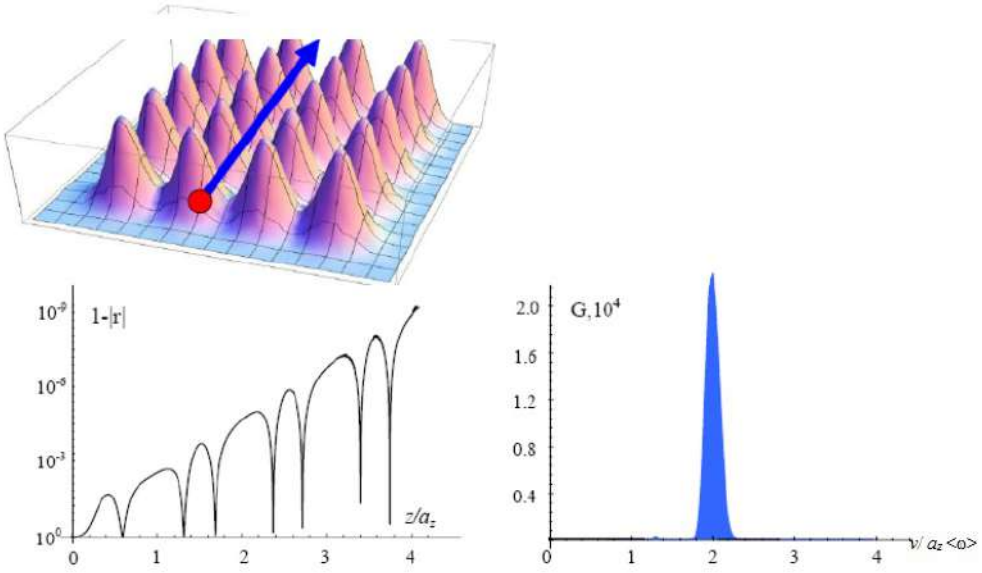

Figure 4. *Top*: the scheme of proton motion through a crystal of lithium; bottom: dependence of the coefficient of correlation $|r|$ at optimal velocity $\nu = 2\,\langle\omega\rangle\ a_z$ versus distance z/a_z and the coefficient of correlation efficiency versus proton velocity in a lithium crystal at $z = 4a_z$.

harmonic oscillator

$$V(x,z) = m_{\rm p}x^2\omega^2(z)/2 = \frac{m_{\rm p}x^2\omega_{\rm max}^2}{2}\sum_{n=1}^{N}\exp\{-[z-(n-1/2)a]^2/u^2\}, \quad |x| \le a_x,\ z \ge 0. \tag{7}$$

In the rest system of the proton such motion corresponds to a nonstationary harmonic oscillator with nonstationary potential energy

$$V(x,z) = \frac{m_{\rm p}x^2\omega^2(t)}{2} \tag{8}$$

and nonstationary characteristic frequency

$$\omega(t) = \omega_{\rm max}\left\{\sum_{n=1}^{N}\exp\left[-((\nu/a_z)t + 1/2 - n)^2K^2\right]\right\}^{1/2}, \quad K = a_z/u, \quad t \ge 0. \tag{9}$$

Here

$$\omega_{\rm max} = \sqrt{8\,\langle V_{\rm max}\rangle\,K/\,a_x^2\,m_{\rm p}\sqrt{\pi}}, \quad \langle V_{\rm max}\rangle \equiv \langle V(x = \pm a_x/2, z)\rangle\,,$$

$$\omega(t=0) = \omega_{\rm max}{\rm e}^{-K^2/8} = \langle\omega\rangle\,\sqrt{K/\sqrt{\pi}}{\rm e}^{-K^2/8},$$

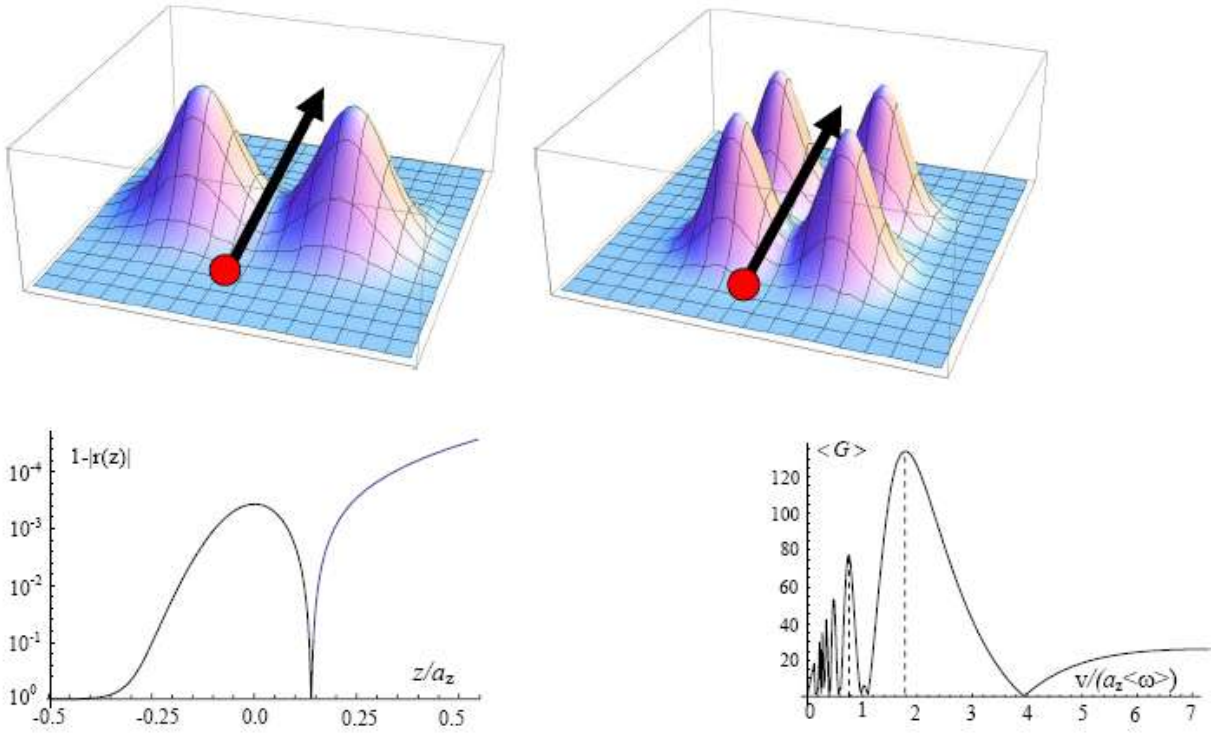

Figure 5. *Top*: the scheme of proton motion through free Li_2 and $(Li_2)_2$ molecules; *bottom*: (left) dependence of the coefficient of correlation $|r|$ at optimal velocity $\nu = 2\langle\omega\rangle a_z$ versus distance z/a_z from center of molecule and (right) the coefficient of correlation efficiency versus proton velocity (both graphs correspond to D_2 molecule at the condition $K = a_z/u = 5$).

$$\langle\omega\rangle = \omega_{\max}\sqrt{u\sqrt{\pi}/a_z} = \omega_{\max}\sqrt{\sqrt{\pi}/K}.$$

The structure of metallic lithium corresponds to a bcc lattice with a period of 3.5 Å, a distance of 3.03 Å between the nearest nuclei and averaged potential of the crystal axis $\langle V\rangle \approx 20$ eV. The average frequency (equal to the channeling frequency in the averaged potential of the crystal channel) calculated with these parameters (a_z =3–3.5 Å, $u \approx$ 0.4–0.5 Å is equal to $\langle\omega\rangle = \omega_{\text{chan}} \approx (5-6)\times 10^{14}$ s^{-1}.

The coefficient of correlation efficiency for the motion of the particle inside the crystal between two axes with periodically arranged atoms has been calculated by solving of Eqs. (6) with the use of explicit time dependence (9) of the variable frequency $\omega(t)$. The calculation has been performed for the initial segment of the trajectory of the particle including four pairs of atoms and with the parameters $K = a_z/u = 4, 5, 6$, which are close to the parameters of the lithium crystal. The results of this calculation for the case $K = a_z/u = 5$ are shown in Fig. 4 (*bottom*).

In this case the optimal condition for CCS formation corresponds to the optimal proton velocity $\nu_{\text{opt}} \approx 2a_z\langle\omega\rangle$ and optimal longitudinal kinetic energy of protons

$$T_{\text{opt}} = \frac{m_{\text{p}}\nu_{\text{opt}}^2}{2} = 2m_{\text{p}}a_z^2\langle\omega\rangle^2 \approx 400-600 \text{ eV} \quad \text{at } K\text{=4-6.} \tag{10}$$

These results are in very good agreement with the experimental data [1] discussed above. At such energy of the proton, the value of the correlation efficiency coefficient is equal to $G_{\max} \approx 23\,000$, which corresponds to giant fluctuations of the kinetic energy $\delta T^{(\min)} \approx 50 - 80$ keV in the transverse direction. At such energy of the proton, the transparency of the Coulomb barrier increases from the initial very small value $D(E) \approx 10^{-50}$ (which corresponds to the energy of 500 eV) to a large value $D(E) \approx 0.01$. In this case the nuclear fusion parameters correspond to the values,

$$\mathrm{d}W_{\mathrm{f}}/\mathrm{d}z = \sigma \langle n_{\mathrm{Li}} \rangle \approx 3 \times 10^{-6}\ \mathrm{cm}^{-1}, \quad W_{\mathrm{f}} \approx \langle L \rangle \sigma \langle n_{\mathrm{Li}} \rangle \approx 10^{-12}, \quad J \approx i_{\mathrm{p}} W_{\mathrm{f}} \approx 10^{3}\ \mathrm{s}^{-1}, \tag{11}$$

which are in good agreement with the experimental data.

It is very important that since CCS are formed very rapidly (within several crystal lattice periods), the deceleration of protons and their collisions with atoms of the crystal lattice can be disregarded.

Let us consider the features of the formation of CCS during the interaction of protons with the molecules of vapor lithium. In the composition of this vapor, about half or more of the lithium atoms are in the form of molecules Li_2 and $(Li_2)_2$ [19]. The distance between the nuclei in the lithium molecule is 2.67 Å. The potential energy in the volume of each of these molecules can be treated as the time-dependent harmonic oscillator for the charged particle moving through a molecule. Consequently, coherent correlated states can be formed in this motion.

This process can be calculated using the same Eqs. (6) and the dependence (7) of the variable frequency $\omega(t)$ in the rest system of the particle under the formal condition $N = 1$. For the comparability of the results for an individual molecule and a crystal, the calculation has been performed for an interval of the space localization of a moving particle in the field of the molecule that corresponds to one period a_z in the crystal. The results of the numerical calculation for $K = a_z/u = 5$ are shown in Fig. 5 (*bottom*).

It follows from these results that the optimal velocity and energy of the particle is slightly different from the same parameters in the case of the crystal and have different values for different ratios of a_z and u. In particular, with the same parameters of atoms as in the case of the lithium molecules, we obtain

$$K = 6, \quad T_{\mathrm{opt}} \approx 400 - 450\ \mathrm{eV}; \quad K = 5, \quad T_{\mathrm{opt}} \approx 500 - 550\ \mathrm{eV}; \quad K = 4, \quad T_{\mathrm{opt}} \approx 600 - 650\ \mathrm{eV}, \tag{12}$$

The physical reason for such difference is associated with the above-mentioned features of the formation of CCS at the modulation $\omega(t) = \omega_0(1 + g \cos\ \Omega t)$ of the parameters of the time-dependent oscillator by monochromatic action. As mentioned above and presented in Fig. 2, the probability of this process is maximal when the modulation frequency Ω is two times greater the average frequency of oscillations of the particle in this potential well in the absence of modulation.

In the case of single molecules, the spectrum of modulation in the coordinate system co-moving with the particle corresponds to the continuous spectrum of a normalized single pulse (for the Gaussian distribution of the potential energy, the spectrum is also Gaussian). In the case of the infinite crystal, the spectrum of modulation consists of a set of discrete lines at frequencies determined by the lattice period and velocity of the particle. All these lines are located inside the spectrum of a single momentum. In the case of a finite fragment of the crystal lattice, each of the discrete spectral lines is broadened and becomes a band with width inverse to the length of the fragment. This spectral analysis obviously indicates that the optimal velocity is that at which the necessary spectral component of the Fourier spectrum of the potential energy is maximal. It is obvious that this condition for different fragments of the potential field at different u values can be satisfied at slightly different velocities and energies of the particle; these values are identical only for a very long lattice.

According to the results presented in Fig. 5, at the ratio $K = 5$ of the considered parameters, which are close to the parameters of the real Li_2 molecule, the coefficient of correlation efficiency for the proton moving at this energy

through the lithium molecule is $G_{\max} \approx 140$. At $K = 6$ the value $G_{\max}$ is even greater. At these $G_{\max}$ values, the cross section and probability of the $(\mathrm{Li}^7, \mathrm{p})$ reaction are very large. This is the result of the fact that in this case it is necessary to take into account that the effective quantization of the moving proton in the time-dependent potential well existing inside the molecule occurs only for the transverse component of the momentum $p_x = p \sin\theta$, which depends on the angle θ of entry of the particle to the space between atoms, and, correspondingly, for the transverse energy associated with this component. We recall that the formation of CCSs concerns these transverse components of the momentum and kinetic energy. If the initial transverse component of the total kinetic energy $T_{\text{opt}} \approx 400 - 600$ eV is, e.g., $T_x = p_x^2/2m_{\mathrm{p}} = 1 - 10$ eV (for this, the proton should be incident at the angle $\theta \approx 2^\circ - 10^\circ$ to the normal to the axis of the molecule), the effective fluctuation of this energy appearing in the process of CCS formation is $\delta T \approx G^2 T_x \approx 10 - 100$ keV. This ensures a high efficiency of the fusion reaction even on individual molecules and is in good agreement with the experimental data for lithium vapor presented in Fig. 1. The real efficiency of fusion can be obtained by averaging over the mutual orientation of lithium molecules and the proton beam.

For a model cluster of two Li_2 molecules, the correlation coefficient in the case of the proton moving with the energy $T_{\text{opt}} \approx 400 - 600$ eV (Fig. 2) at the same real value $K = 6$ is as high as $|r|_{\max} \approx 0.999999$, which corresponds to the correlation efficiency $G_{\max} \approx 700$ and also very large efficiency of fusion.

It is easy to see that other features of LENR (first of all the absence of daughter radioactive isotopes and very strong selection of channels of nuclear reactions) also follow from the peculiarities of CCS. Different aspects of these features were considered in detail in our earlier works [11,12,15–18].

In particular, from the basic relations (4) it follows that the possibility of producing LENR with virtual kinetic energy $\delta E \equiv \delta T_{|r|\neq 0}$ is limited by the conservation laws for the entire system. Very important is the fact that this virtual energy "exists" in the given system (that is, it can have a certain influence on different processes) a finite time δt. As a consequence, any process using δE can be produced only if during the reaction carried out by this virtual energy, the reaction energy ΔE that is not less than δE is released and the time of "return" to the system under consideration of this virtual energy (in fact, the duration of the reaction with the release of energy) does not exceed the value of δt.

This result, with respect to the nuclear reaction, corresponds to the fact that the total time of the reaction T_{total} (including the time of approach of the particle to the barrier t_1, the duration of the passage through the barrier t_2 and the time of the reaction itself with the release of energy T_{reaction}) should not exceed δt. This requirement, taking into account the very short duration δt of a large fluctuation amplitude $\delta T_{|r|\to 1}$, imposes very stringent conditions on such processes and automatically excludes the possibility of nonoptimal reactions. These conditions fully explain the complete prohibition on reaction (3) and "permission" for reaction (1).

Let us take as an estimate that for the rapid production of these reactions it is necessary for proton to have the energy $\delta E \approx 10$ keV. In the case of using the Heisenberg uncertainty relation $\delta E\, \delta t_{r=0} \geq \hbar/2$ such fluctuation can exist for a time $\delta t_{r=0} \approx \hbar/2\delta E \approx 5 \times 10^{-21}$ s. At this energy, the minimum total reaction time is equal to $T_{\text{total}} = T_{\text{reac}} + t_1 + t_2 \approx T_{\text{reac}} + L(\delta E)/\nu(\delta E) \approx 10^{-18}$ s.

It can be seen from the reaction schemes (1) and (2) that for such value of T_{total} the necessary condition $T_{\text{total}} < \delta t_{r=0}$ is not satisfied for both reactions and they are totally impossible in "usual" (noncorrelated) state.

In the correlated state, with an achievable value $|r| \approx 0.99999$, the same energy fluctuation $\delta E \approx 10$ keV can exist during $\delta t_{r=0.99999} \approx \hbar/2\delta E\sqrt{1-r^2} \approx 2.5 \times 10^{-18}$ s. Comparing this value with the total duration $T_{\text{total}} \approx 10^{-18}$ s of reaction (1) $\mathrm{Li}^7 + \mathrm{p} = 2\mathrm{He}^4$, we come to the conclusion that $T_{\text{total}} \approx 10^{-18}$ s $< \delta t$ (i.e. the total reaction time is less than the fluctuation time that stimulates this reaction), and the flow of such a reaction is consistent with the law of conservation of energy and the corresponding uncertainty relation.

In contrast, for reaction (2), the opposite condition $T_{\text{total}} \approx 10^{-13}$ s $\gg \delta t$ takes place and such reaction is absolutely impossible due to the formation of CCS.

These results fully coincide with the data of both the above-mentioned paper [1] and very detailed experiments [20]

conducted for 32 days in Lugano for the examination of the A. Rossi installation, in which very efficient processing of the Li^7 isotope was observed, which is characterized by a short reaction time, and complete absence of reactions involving the Li^6 isotope.

Similarly, it is easy to show that the same selection rule prohibits the production of LENR in reaction channels involving any other isotopes and elements that have a longer reaction time exceeding δt. It is obvious that, taking into account the smallness of δt even in systems with a large correlation coefficient, the reactions passing through the stage of formation of long-lived radioactive isotopes fully fall under this prohibition.

In conclusion, it should be noted that in the framework of a general methodological approach the use of CCS allows us to uniquely describe, calculate and predict the main features of nuclear reactions at low energy of interacting particles. Such analysis is fully applicable to nuclear processes occurring both in "standard" environments for such experiments (gas, metal hydrides, low-pressure plasma, liquid, crystals) and in more exotic objects and systems (in biological macromolecules and their nonstationary ensembles [21,22], in a fluid in the presence of cavitation phenomena [23], in active Mossbauer spectroscopy [24], in astrophysics in the process of combined gravitational-Coulomb collapse [25] and even under the action of a pulsed magnetic field of thunderous times series with the participation of deuterium in the natural isotopic abundance of the atmosphere and subsequent generation and detection of neutrons [17,26–28].

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